HUMAN-MACHINE COOPERATION: Adaptability of shared functions between Humans and Machines - Design and evaluation aspects

Marie-Pierre Pacaux-Lemoine

Université Polytechnique HAUTS-DE-FRANCE

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Présentée par :

Marie-Pierre PACAUX-LEMOINE

Docteur en Automatique des Systèmes Industriels et Humains

HUMAN-MACHINE COOPERATION

Adaptability of shared functions between Humans and Machines
Design and evaluation aspects

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Max MULDER	Pr.,TU Delft, Netherlands	Rapporteur
Gilles COPPIN	Pr., IMT Atlantique, Brest, France	Rapporteur
Bernard GRABOT	Pr., ENIT, Tarbes, France	Rapporteur
Tetsuo SAWARAGI	Pr., University of Kyoto, Japan	Examinateur
Marie BABEL	MCF HDR, INSA, Rennes, France	Examinateur
Jordan NAVARRO	MCF HDR, Université de Lyon, France	Examinateur
Frank FLEMISCH	Pr., RWTH, Aachen, Germany	Invité
Patrick MILLOT	Pr., UPHF, Valenciennes, France	Promoteur

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Une pensée particulière pour mes parents, plus de ce monde depuis trop longtemps, toujours à mes côtés dans les défis que je souhaitais relever, encore aujourd'hui de par mes souvenirs …

Mes remerciements s'adressent en premier lieu à mon mari, Patrick, pour son soutien sans relâche et ses commentaires pertinents pour atteindre cet objectif d'obtenir l'Habilitation à Diriger des Recherches, et bien d'autres objectifs ! ces remerciements s'étendent naturellement à mes filles, Ninon et Elane, pour leur patience et leur aide ; pas simple d'avoir une mère souvent aux quatre coins du monde et parfois trop focalisée sur sa recherche !

Je remercie tout particulièrement les Professeurs Thierry-Marie Guerra, Eric Markiewicz et Patrick Millot de m'avoir proposé, encouragé, puis donné les moyens de soutenir l'Habilitation à Diriger des Recherches. Un grand merci également au Professeur Damien Trentesaux pour les discussions houleuses mais constructives que nous avons pu avoir et que j'espère nous aurons encore.

Je tiens également à remercier tous les collègues et amis de l'UPHF qui se reconnaîtront (BIATSS, enseignants-chercheurs, doctorants, post-doctorants et étudiants) pour leurs encouragements, surtout au cours des derniers mois avant la soutenance.

I would like to thank the defense committee to have accepted to be involved in the evaluation of my work, work they already partly knew after discussions during PhD defenses or international conferences.

General introduction

The objective to obtain the "Habilitation à diriger des recherches" is not a usual way for a French research engineer to pursue a carrier. Nevertheless, since my PhD in 1998, the LAMIH gave me the opportunity to conduct research activities in parallel to the engineering activity. Such an organization allowed being close to system design, experimental environment and system users, as well as the research environment and the ability to debate with researchers in conferences and research groups. Therefore, the present report deals with my Curriculum Vitae, the state of the art in Human-Machine System, two main scientific contributions and perspectives. The first scientific contribution tackles conceptual aspects with the proposal of Human-Machine Cooperation models. The second one details methodological aspects with the design and evaluation of Human-Machine Systems. My activities were mainly focusing on research; however, I had also the opportunity to have a teaching activity. I was temporary assistant professor and then I have been involved in training institutes to oversee students during internships and projects, as well as by teaching courses in particular about research projects.

Therefore, thanks to many discussions with colleagues from foreign and French labs, LAMIH and students, I have always been wanted to go deeper in the scientific approach to design and evaluate Human-Machine System, but at the same time, to be more generic, in the models of Human-Machine Cooperation we proposed. The present report is also the opportunity to make a synthesis of my work and to take advantage of the presentation of the wide evolution in the Human-Machine System design to propose several tracks to continue to improve this research direction, but new complementary directions too.

The document is organized around six chapters:

- Chapter 1 presents my Curriculum Vitae, *i.e.* my academic background, as well as my research and teaching activities since 1994.
- Chapter 2 summarizes the state of the art in Human-Machine System and gives the key definitions and some lacks identified in the past and current research studies.
- Chapter 3 provides my contributions regarding improvements in terms of models to define cooperation between human and automation, adaptability of cooperation according to several criteria and cooperation between several humans and several automated systems.
- Chapter 4 proposes to use cooperation models proposed in the Chapter 3 to develop a method for the design of Human-Machine System, and several tools to conduct evaluations of the designed system according to experimental context.
- Chapter 5 deals with the next steps of the research and teaching activities. Several ways to improve and evaluate the models of cooperation have already been identified, especially within the framework of cooperation with several other labs, as well as an interesting connection with teaching activities and the involvement of students in our research work.

Chapter 1. Presentation of research, teaching and administrative activities

1.1 Academic Background

- Research Engineer in the Automation department of LAMIH UMR CNRS 8201 (Laboratory of Industrial and Human Automation control, Mechanical engineering, Computer Science), université Polytechnique Hauts-de-France, UPHF, previously University of Valenciennes and Hainaut-Cambrésis (UVHC), France, 1998
- PhD: Human-Machine Cooperation for complex process, UVHC, 1998
- Master in Industrial computing and production engineering, UVHC, 1992
- Undergraduate studies in Mathematics and Physics (Diplôme d'Etudes Universitaires Générales in Sciences, UVHC), UVHC, 1989

1.2 Research activity

My research activity consists in participating and supervising research projects, supervising PhD students and engineers involved in these projects. In parallel to projects, I contribute to research groups and lead parts of these groups.

1.2.1 Projects

My research activities have been mainly based on the framework of national and industrial projects conducted since my PhD. With the benefit of hindsight, research projects can be presented according to two dimensions based on the concepts extracted from these activities. The first dimension is the decisionl level which deals with the type of activity implied in the Human-Machine System, depending on the level of abstraction and the temporal constraints of the tasks, but also on the hierarchical organisation (in particular the authority management and sharing) of the Human(s)-Machine(s) Systems. The second dimension relates the levels of automation of the systems that have been designed during these projects. This dimensions is split into two parts, dealing with the Know-How (KH) and the Know-How-to-Cooperate (KHC) implemented in the Human-Machine System.

Therefore, Fig. 1 presents all projects I took part or I am still taking part according to these dimensions. The figure highlights the focus of the projects and the kind of concept the project studied, dealing more with the cooperation between levels of activity, or focusing on communication tools with the Know-How-to-Cooperate (KHC), or defining automated functions and their allocation with the Know-How (KH). While the older projects only responded to few parts on these dimensions, current projects involve more and more aspects from a low control level close to the operative part of the Human-Machine System, to higher decisional levels discussing Human(s)-Machine(s) organisations for a longer-term vision of the activity.

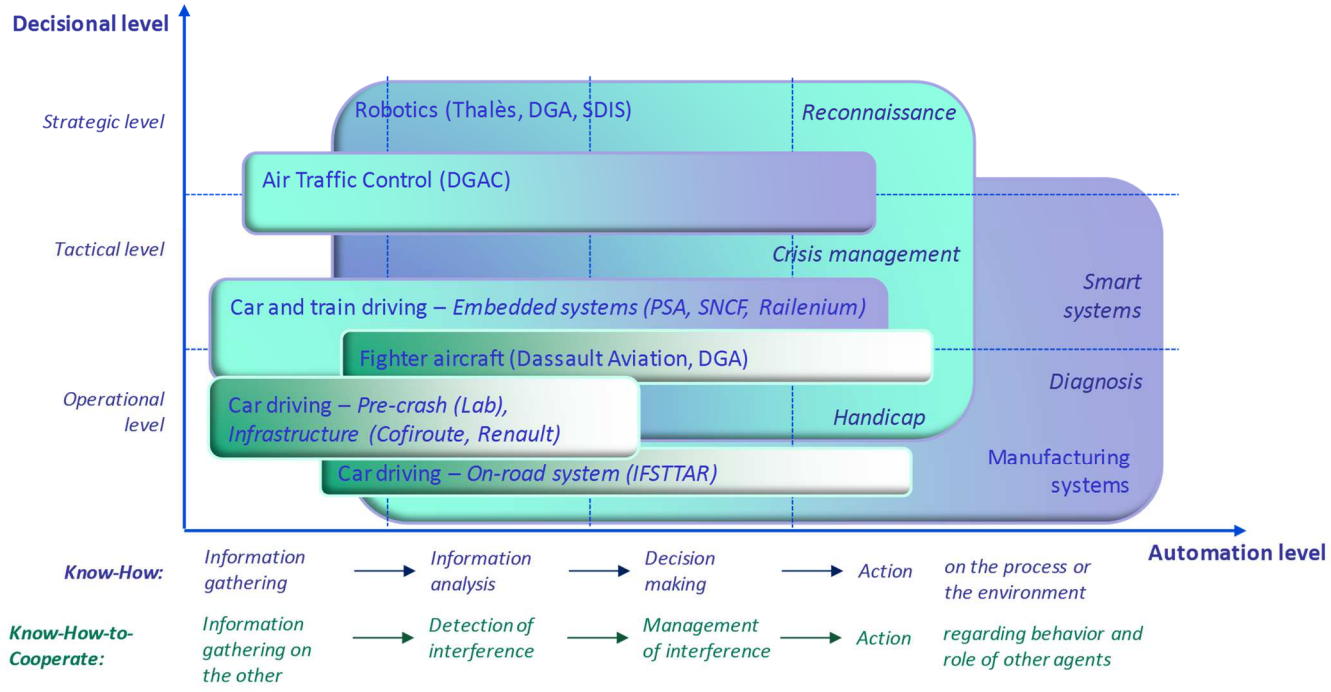

Fig. 1 Projects presented according to their objective in terms of decisional levels to be assisted and the level of automation implemented defined according to Humans and Machines respective KH and KHC

Several projects were or are conducted in several domains of application. Such an ability allows the evaluation of the models and the systems we designed with different contexts, different types of human operator and different constraints. The project names are listed below, followed by the particular topic I studied. Further details are provided all along the presentation of the research activity, as well as at the end of the manuscript in the section Chapter 7, in the appendix.

- 2019-2022: FEDER project, Smart Fashion 4.0: Design of smart garment factory in a 4.0 context: from fashion trend to design and manufacturing (cf. §7.6.3).
- 2017-2021: TC-RAIL project: Train remote control (Railenium, SNCF, Thales C&S, Actia Telecom, CNES) (cf. §7.6.3).
- 2017-2021: HUMANISM project: Human-Machine Cooperation for Intelligent Manufacturing System, (cf. §7.6.2).
- 2014-2017: SUCRé project: Human-Human and Human-Robots Cooperation in hostile environment (head of project, cf. §7.4.3).
- 2013-2016: COCOVEA project: Driver - automated vehicle cooperation (PSA, Valeo, Continental), (cf. §7.2.1).
- 2007-2012: ADEXEC project: Approche de Détection et d'Explication d'Erreur de Commande par filtrage robuste, GIS 3SGS, (cf. §7.6).
- 2005-2010: SARI Project: Automated Supervision of the Road to Inform drivers and managers (IFSTTAR), (cf. §7.2.2).
- 2006-2009: TAROT Project: Definition of Autonomy modes for human-robot cooperation, DGA (French Defence), Thalès, (cf. §7.4.2).

- 2004-2008: ST2 Project: Design and evaluation of safety systems during risky and pre-crash situation, (cf. §7.2.3).
- 2002-2005: ARCOS Project: Research Action for Safe Driving Contribution to adaptive cruise control design and evaluation, (cf. §7.2.1).
- 2002-2003: Project with Cofiroute and Renault: Studies dealing with the design of an unusual tunnel for automobile, (cf. §7.2.4).
- 1998-2001: Project with Dassault Aviation: Studies dealing with Human-Human cooperation in the cockpit of two-seater fighter aircraft, (cf. §7.3).
- 1992-1998: SPECTRA Project, dealing with the design and evaluation of assistance system to detect and manage aircraft conflicts, CENA (Centre d'Etudes de la Navigation Aérienne), DGAC (French Civil Aviation), (cf. §7.1).
- 1992-1994: SWIFT Project: Specification for working positions in future air traffic control, Eurocontrol, (cf. §7.1).

1.2.2 Research supervision

1.2.2.1 Supervision of PhD students

I was co-supervisor of two PhD students, and currently co-supervisor of two other PhD students. Nevertheless, I was involved in the staff working with five other PhD students, Julien Ordioni (ST2 project, S. Debernard, J.-C. Popieul, 2004, not defended), Nicolas Tricot (ARCOS project, 2005, P. Millot, J.-C. Popieul), Jean-Marc Girard (ST2 – phase 2 project, 2007, P. Loslever, J.-C. Popieul), Anthony Loiselet (Dassault aviation – DGA project, R. Amalberti, J.-M. Hoc, not defended), Stéphane Zieba (TAROT project, 2009, F. Vanderhaegen, P. Polet).

Defended PhDs:

Doctor:	Last name:	HABIB	First name:	Lydia
Thesis title: (SUCRé project)	*Niveaux d'automatisation adaptables pour une coopération homme-robots*, Adaptable levels of automation for Human-Robots Cooperation			
Start date:	November 2015	Defense date :	December 2019	
Involvement:	70%	Co-supervisors :	Patrick MILLOT (30%, PR, UPHF)	
Duration of the thesis:	50 months			
Current work-status:	Post-doc at UPHF			
Jury members:	Hind BRIL-EL HAOUZI (PR, Université de Lorraine), Pascal BERRUET (PR, Université de Bretagne Sud), Marie BABEL (MCF-HDR, Institut National des Sciences Appliquées), Philippe PUDLO (PR, Université Polytechnique Hauts-de-France), FOUCRIER Laurent (Commandant, COMSIC du NORD)			
Main scientific output:	Habib L., Pacaux-Lemoine M.-P., Millot P. (2018). Human-robots team cooperation in crisis management mission. *IEEE International Conference on Systems, Man, and Cybernetics, Miyazaki, Japan, October*			

Doctor:	Last name:	DUQUESNE	First name:	Ludovic
Thesis title: (SARI project)	*Une approche d'aide multicritère à la décision pour l'acceptation d'une signalisation routière dynamique*, Approach of multicriteria decision aid for the acceptability of dynamic road signs			
Start date:	October 2005	Defense date :	June 2009	
Involvement:	34%	Co-supervisors :	Patrick MILLOT (33%, PR, UPHF) Igor CREVITS (33%, MCF UPHF)	
Duration of the thesis:	45 months			
Jury members	Anne-Marie JOLLY (PR, Université d'Orléans), Gaëtan LIBERT (PR, Faculté Polytechnique de Mons), Marie-Line GALLENNE (Researcher at Laboratoire Central des Ponts et Chaussées).			
Main scientific output:	Duquesne, L., Millot, P., Pacaux-Lemoine, M.-P., & Crevits, I. (2009). APPROACH OF MULTICRITERIA DECISION AID FOR THE ACCEPTABILITY OF DYNAMIC ROAD SIGNS. *28th European Annual Conference on Human Decision-Making and Manual Control*.			

Ongoing thesis:

Doctor:	Last name:	BERDAL	First name:	Quentin
Thesis title: (HUMANISM project)	*Conception d'un système manufacturier intelligent basée sur les principes de la cooperation Homme-Machine;* Designing Intelligent Manufacturing Systems through Human-Machine Cooperation Principles			
Start date:	February 2018	Defense date :		
Involvement:	40%	Co-supervisors :	Damien TRENTESAUX (30%, PR, UPHF), Christine CHAUVIN (30%, PR, Université de Bretagne Sud)	
Main scientific output:	Berdal Q., Pacaux-Lemoine M.-P., Trentesaux D., Chauvin C. (2019). Human-Machine cooperation in self-organized production system: a point of view. Borangiu, Trentesaux, Thomas, Cavalieri, *Service Orientation in Holonic and Multi-Agent Manufacturing, 803, Studies in computational intelligence, Springer, pp. 123-132, january*			

Doctor:	Last name:	MAJIDAN	First name:	Mehran
Thesis title: (SMART FASHION 4.0 project)	*Méthode de conception et d'évaluation de configurations dynamiques d'organisations homme(s)-machine(s) pour la confection 4.0,* Design and evaluation method to set-up Human(s)-Machine(s) organizations in garment factory 4.0			
Start date:	March 2020	Defense date :		
Involvement:	33%	Co-supervisors :	Frédéric VANDERHAEGEN (33%, PR, UPHF), Sébastien THOMASSEY (33%, PR, ENSAIT)	

1.2.2.2 Member of PhD jury

Doctor:	Last name:	ROBACHE	First name:	Frédéric
Thesis title:	*Évaluation sur simulateur de conduite du comportement humain en situation de pré-crash : application à l'amélioration des airbags ;* Pre-crash phase analysis using a driving simulator. Influence of atypical position on injuries and airbag adaptation			
Defense date :	March 2017			
Co-supervisors :	Pascal DRAZETIC (PR, UPHF), Hervé MORVAN (IR, UPHF)			

1.2.2.3 Supervision of project

I was most of the time involved in the different phases of construction of all the projects, but I initiated or co-leaded four projects: SARI, SUCRé, HUMANISM, SMART FASHION 4.0.

I contributed, on last November, with German and Japanese colleagues to the initiation of the proposal construction to the European-Japanese call "Programme IA ANR-DFG-JST", and we submitted the proposal entitled "AiAIDo: A way towards a good, *i.e.* controllable, transparent, trustable, fair and cooperative AI in smart mobility" to the three research agencies. We are waiting for the result on March.

1.2.2.4 Supervision of research group

I am co-leader of the Human-Machine System theme of the Regional Research Group in Integrated Automation and Human-Machine System (GRAISyHM) since 2014. My involvement in this group gave me the opportunity to identify researchers from the Hauts-de-France department who would like to be involved in Human-Machine System topic, and to cooperate with them to propose regional projects (SUCRé, Smart Fashion 4.0).

I presented my research work within the framework of:

- the CNRS research group GdR MACS (Modelling, Analysis, and Control of dynamic Systems): Pacaux-Lemoine M.-P., Trentesaux D. (2018). L'Humain, l'organisation et les machines : quelles coopérations pour quels objectifs ? 26èmes journées Sciences et Techniques de la Production [102].
- the GIS GRAISyHM (Groupe d'Intérêt Scientifique de recherche en Automatisation Intégrée et Systèmes Homme-Machine) – Human-Machine System theme: Cognitive Work Analysis vs. Human-Machine Cooperation in HUMANISM project, « Human & Industry 4.0 » [101].

1.2.2.5 International mobility

I had the ability to share my research work with Laboratory for Cognitive Systems Science of Tsukuba (Japan) within the framework of the (Partenariat Hubert Curien) PHC SAKURA, 2009-2010. I proposed to change the approach regarding the definition of the levels of automation during a seminar organized with Prof. Inagaki and Prof. Itoh [115].

I took part in the European Research Network HAMASYTI (Human-Machine Systems in Transportation and Industry) with England, Netherland, Germany, France, 2010-2013. I was involved in the proposal of the MATE project involving TU Delft, Univ. Aachen, Univ. Leeds, UPHF-LAMIH, UTC-HEUDIASyC and URCA-CReSTIC. It consisted in developing a mobility support tool dedicated to visually impaired persons by using NTIC. It aimed to design a new smart stick prototype for assisting navigation in a dynamic urban environment by taking into account safety and individual constraints. It was submitted to Horizon 2020 - Research and Innovation Framework Programme (H2020-FETOPEN-1-2016-2017). It was well evaluated but not selected.

I was also involved in the Joint research lab on Risk Management in Life Critical Systems (Partner University Fund between France/LAMIH-TEMPO and USA/FIT, 2012-2015) and I presented my research work at Summer and Winter Schools organized within the framework of the lab (cf. §8.8) [104][105][106][108][110][112].

I won a mobility grant in order to increase the cooperation between France and Germany (2019). The project called "CoopInEuro" dealing with Human Cyber-Physical Systems cooperation in European Industry allowed to go deeper in the discussion with Fraunhofer (Watchberg) and to make contact with the European Astronaut Centre — Directorate of Human Spaceflight and Robotic Exploration Programmes, Cologne. I gave one presentation in each institute [99][100].

Since February 2020, I am involved for 3 years in a technical team of the Science and Technology Organization (STO) of the North Atlantic Treaty Organization (NATO, HFM-RTG 330) on “Human Systems Integration for Meaningful Human Control over AI-based systems".

1.3 Scientific output

My involvement in several projects and debates conducted during conferences or in research groups gave me the opportunity to propose: 15 articles in journals, 72 papers in conferences, 5 book chapters and 35 reports. The references are listed at the end of the document (cf. part Chapter 8: Appendix 2) and most cited papers are presented in the Table 1.

Table 1 Most cited papers (GoogleScholar, February 2020)

Article in journal or conference	Number of citations
Hoc J.-M., Lemoine M.-P. (1998). Cognitive evaluation of human-human and human-machine cooperation modes in air traffic control. International Journal of Aviation Psychology, 8, pp. 1-32	117
Pacaux-Lemoine M.-P., Debernard S. (2002). A Common Work Space to support the Air Traffic Control. Control Engineering Practice, A Journal of IFAC, 10 (5), pp. 571-576	92
Pacaux-Lemoine M.-P., Trentesaux D., Zambrano rey G., Millot P. (2017). Designing Intelligent Manufacturing Systems through Human-Machine Cooperation Principles: A Human-Centered Approach. Computers & Industrial Engineering, 111, pp. 581-595	75
Millot P., Pacaux-Lemoine M.-P. (1998). An attempt for generic concepts toward Human Machine Cooperation. IEEE SMC, California, San Diego, USA, october	69
Hault-Dubrulle A., Robache F., Pacaux-Lemoine M.-P., Morvan H. (2011). Determination of pre-impact occupant postures and analysis of consequences on injury outcome. Part I: A driving simulator study. Accident Analysis and Prevention, 43(1), pp. 66-74, ISSN 0001-4575.	51
Auberlet J.-M., Pacaux-Lemoine M.-P., Anceaux F., Plainchault P., Rosey F. (2010). The impact of perceptual treatments on lateral control: A study using fixed-base and motion-base driving simulators. Accident Analysis and Prevention, 42, pp. 166-173	51
Lemoine M.-P., Debernard S., Crévits I., Millot P. (1996). Cooperation between humans and machines: first results of an experimentation of a multi-level cooperative organisation in air traffic control. Computer Supported Cooperative Work, 5 (2), pp. 299-321	51
Auberlet J.-M., Rosey F., Anceaux F., Pacaux-Lemoine M.-P., Aubin S., Briand P., Plainchault P. (2012). The impact of perceptual treatments on driver's behavior: From driving simulator studies to field tests—First results. Accident Analysis and Prevention, 45, pp. 91-98	47
Millot P., Pacaux-Lemoine M.-P. (2013). A common Work Space for a mutual enrichment of Human-machine Cooperation and Team-Situation Awareness. 12th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design, and Evaluation of Human-Machine Systems, Las Vegas, Nevada, USA, august	38
Flemisch F., Abbink D., Itoh M., Pacaux-Lemoine M.-P., Wessel G. (2016). Shared Control Is the Sharp End of Cooperation: Towards a Common Framework of Joint Action, Shared Control and Human Machine Cooperation. IFAC Analysis, Design and Evaluation of Human-Machine Systems, Kyoto, Japan, august	36
Pacaux-Lemoine M.-P., Debernard S., Godin A., Rajaonah B., Anceaux F., Vanderhaegen F. (2011). Levels of automation and human-machine cooperation: Application to human-robot interaction. 18th IFAC World Congress, Milano, Italy, august	34
Pacaux-Lemoine M.-P., Itoh M. (2015). Towards vertical and horizontal extension of shared control concept. IEEE International Conference on Systems, Man, and Cybernetics, Hong Kong, China, october	26
Lemoine M.-P., Crévits I., Debernard S., Millot P. (1995). Men-machines cooperation: toward an experimentation of a multi-level cooperative organization in air-traffic control. International Workshop on the design of cooperative systems, Antibes-Juan les pins. France, pp. 405-423, january	20
Pacaux-Lemoine M.-P., Loiselet A. (2002). A common work space to support cooperation in the cockpit of a two-seater fighter aircraft. M. Blay-Fornarino, A.M. Pinna-Dery, K. Schmidt, & P. Zaraté, Cooperative systems design: a challenge of mobility age, IOS Press, Amsterdam, North-Holland, pp. 157-172, january	19

I was co-editor of the "Special issue on shared and cooperative control, Cognition" in the journal "Technology & Work" with Flemisch F., Abbink D. and Itoh M. (2019). Another special issue is currently proposed on "Human and Industry 4.0" in the same journal and with F. Flemisch.

In order to push the Human-Machine cooperation approach at the international level, I organized special sessions at:

- IFAC HMS (2019) about "Towards symbiotic and cooperative automation, autonomy in human-machine systems: Layers of cooperation": 11 articles
- IEEE ICPS (2018) about "Towards Human-Machine Cooperation in Industrial Socio-Cyber-Physical Systems": 12 articles
- IEEE SMC (2017) about "Shared and Cooperative Guidance and Control among humans and machines": 6 articles.

Since 2020, I take part to the technical committee of the new conference IEEE International Conference on Human-Machine System, and I propose several articles. One of the objectives is to discuss some new topics of my research and to debate with experts of the HMS design and evaluation.

Review and referee requests

I am reviewer of several journals and take part to the committee board of several conferences:

- Journals (IF: Impact Factor; Year (Number of evaluation):
  - Cognition Technology & Work (IF: 1.188): 2015 (1), 2017 (2), 2018 (3)
  - Computers in Industry Journal (IF: 4.769): 2015 (1) and 2019 (1)
  - European Journal of Industrial Engineering (IF: 1.217): 2017 (1)
  - ACM Transactions on Human-Robot Interaction (IF: 3.081): 2014 (1)
  - IEEE Transactions on Systems, Man and Cybernetics: Systems (IF: 7.351): 2016 (1), 2017 (1)
  - IEEE Transaction on Vehicular Technology (IF: 5.339): 2018 (1)
  - International Journal of Computational Intelligence Systems (IF: 2.153): 2016 (1)
  - International Journal of Production Research (IF: 3.199): 2016 (1)
  - Journal of Manufacturing Systems (IF: 3.642): 2017 (1)
  - Paladyn Journal of Behavioral Robotics (IF: 1.707): 2018 (1)
  - Robotics (IF: 1.53): 2018 (1)
- Conferences:
  - International Conference on Uncertainty Modelling in Knowledge Engineering and Decision Making: 2016 (1)
  - IEEE International Conference on Human-Machine Systems: 2020 (5)
  - IEEE International Conference on Systems, Man and Cybernetics: 2014 (2), 2015 (2), 2017 (2), 2018 (2)
  - IEEE International Conference on Industrial Technology: 2018 (3)
  - IFAC Human-Machine System: 2013 (1), 2019 (2)
  - IFAC World Congress: 2014 (1), 2017 (2), 2020 (2)
  - Road Safety and Simulation Conference: 2013 (4)

1.4 Teaching activity

As teaching is not the main activity of Research Engineer, in the French University organization, I am allowed to give courses and lectures, as a second job. In this context, the number of teaching hours is lower than these of professors or assistant professors.

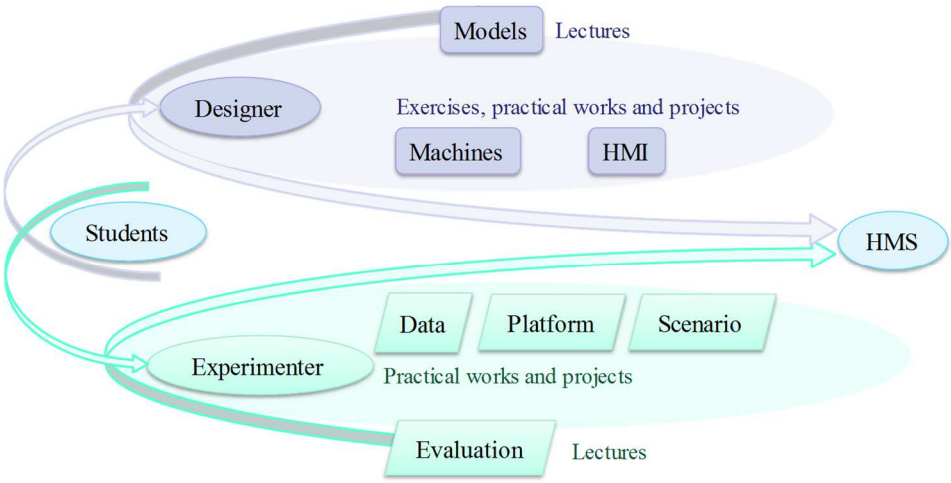

Fig. 2 Teaching activity

However, I was pleased to teach our way to design and evaluate Human-Machine Systems. The two axes, design and evaluation were addressed separately or together, regarding the type of course (lecture, exercise, practical work and project) and the number of hours allocated to courses. Therefore, students are trained to be designer (purple part of Fig. 2), they learn several types of model proposed by industry and literature, how designing machines by programing software and hardware systems, as well as Human-Machine Interface.

In parallel, they are trained as experimenter to be able to evaluate the HMS they designed, not only the technical validity, but also the usefulness of their systems through data analysis and scenario (green part of Fig. 2). They learn to design a scenario, to identify and implement recordings, to analyze data and present results in order to evaluate the system they designed. However, they are also participants to experiments in order to evaluate systems designed by other students.

1.4.1 Institutes

I am involved in four institutes of Université de Valenciennes et du Hainaut-Cambrésis which became Université Polythechnique Hauts-de-France in 2018. My teaching activities from 1994 to today are:

- IUT GEII, Institute of Technology about Electrical Engineering and Industrial Computer Science (Institut Universitaire de Technologie en Génie Electrique et Informatique Industrielle), I give lectures and in Licence 2 which is the 2nd year of bachelor and oversee internship in industry.
- ISTV, Faculty of Technology of Valenciennes (Institut des Sciences et Techniques de Valenciennes), I give practical works and lectures in Licence 2 and 3, 2nd and 3rd year of bachelor, as well as in Master 1 and 2.

- ENSIAME, Engineering school on software, control, mechanical, energy and electronic engineering (École nationale supérieure d'ingénieurs en informatique, automatique, mécanique, énergétique et électronique), I give lectures and oversee projects in the 2nd and 3rd years, *i.e.* Master 1 and 2.
- FSMS, Faculty of Sport Professions and Sciences (Faculté des sciences et métiers du sport), I gave lecture and oversaw projects.

The three last institutes (ISTV, ENSIAME, FSMS) merged in September 2019 to form the INSA Hauts-de-France, National Institute of Applied Sciences (Institut National des Sciences Appliquées), as a French engineering university, part of the Engineering Group INSA.

1.4.2 Courses

I was temporary assistant professor during two years from September 1996 to August 1998, and I had about 100 teaching hours each year.

I was temporary teacher from September 2011 to today as presented in the Table 2.

Table 2 Number of effective hours done in the four institutes

Years	Lectures	Exercises	Practical works	Projects	Number of hours
2019-2020	4,5h	36h	36h	32h	108,5
2018-2019	-	27h	36h	32h	95
2017-2018	6h	21h	-	22h	49
2016-2017	-	20h	35h	-	55
2015-2016	-	20h	-	6h	26
2014-2015	-	20h	-	7,5h	27,5
2013-2014	-	20h	-	9h	29
2012-2013	-	10h	-	9h	19
2011-2012	-	-	-	9h	9

- Lectures:
  - Design and evaluation of automated systems
  - Human-Robot Cooperation
  - Cooperation between automated system and human science designers

- Exercises:
  - Design automated systems regarding Human factors

- Practical work:
  - ADA and C programming environment
  - Grafcet (PLC: Programmable Logical Controller)

- Oversee of students in project at the university, some examples:
  - Robot design (Robot C)
  - Communication between robots (XBee, Bluetooth)
  - Communication Smartphone, Robot (App Inventor)
  - Human-Machine Interface (Visual C++, Qt)
  - Mixed-Initiative Experimental (MIX) testbed (from US Army Research Laboratory)
  - Car driving simulator assistance systems (C++)
  - Smart garments (Arduino, XBee)

- Oversee of students in internship in industry on control and supervision, some examples: Renault, SPIE, William Saurin, AGC Boussois, Nestlé.

Example of course dealing with supervision, tought to the students of bachelor diploma last year.

- Lecture on Human(s)-Machine(s) systems design and evaluation
  - models, methods, examples in the framework of several projects
- Exercises
  - students play "the designer": using models and methods to design IHM in the case of the supervision of a production cell loaded/unloaded by robots
- Practical work
  - students play "the user": experimenting a human-machine system designed by someone else within the same framework as exercises

1.4.3 Referee

I am the referent person for students of UPHF/INSA to apply for studies and an internship at the University of Tsukuba in Japan.

1.5 Administrative activity

I took part during 3 years (2012-2015) at the Joint Committee of the University (CPE: Commission Paritaire d'Etablissement) to analyze the possibilities for university employees to be promoted at the national level for their career advancement.

I was member of a HCERES committee (Haut Conseil de l'évaluation de la recherche et de l'enseignement supérieur), for the Research Evaluation department (Département d'Évaluation de la Recherche), for the evaluation of a French lab in 2017.

Introduction to research

Over the last centuries, we have experienced scientific, technological and societal progress that has enabled the design of machines with increasing abilities and autonomy. Such an evolution must be attached to real advances for humans as well as for mankind. This requires a conscious distribution of roles and control between humans and machines. Machines can be more than just either fully automated or manually controlled; they can work together with humans at different levels of assistance and automation in a hopefully beneficial cooperation. One way for studying and reaching such a beneficial cooperation has been explored within the framework of Human-Machine Cooperation. It is one of the main topics studied by the Automation department of LAMIH for over thirty years (P. Millot & Willaeys, 1985; Patrick Millot, 1988). Many works managed with various investigations and exchanges with research partners from different disciplines, including automation, computer sciences, cognitive and social psychology, have allowed exploring several ideas to build efficient and desired cooperation between human and machine.

The main global objective of the research is to answer the question: how might it be possible to provide humans with machine in a way that a kind of "complicity" could emerge from their interaction? Human-machine cooperation principles have been the main means used to study and find the best combination of Human and machine capabilities to meet human needs. My background in automation initially led to take into consideration only human and machine competences to complete the mandated tasks. Nevertheless, the time spent with professional human operators demonstrates to what extent other types of competence and skills have to be involved in the design of efficient and well-accepted cooperation. Therefore, we identified and modeled other aspects of competence. These aspects focus on cooperation and we defined the *Know-How-to-Cooperate*. It is the ability of human and machine to work with each other in order to reach a common goal and to facilitate the task of the other. In the present report, we use the definition of the *Know-How-to-Cooperate* to study human-machine cooperation, an ability usually applied to human-human cooperation, when people are working more or less efficiently and amicably with each other. Thinking of these aspects brings many examples to mind.

Literature usually highlights asymmetry between the human and the machine. Nevertheless, with the increase of machine ability, more and more examples show that when machine suits human needs well, symmetry may increase. This is the reason of our willingness to build up similar models for the human and the machine. We defined the model of a cooperative agent, an agent being a human or a machine. We define an agent according to two abilities. The first ability is the *Know-How*, which deals with the ability to control a part of the process without any help from other agents. It is the capability and the capacity of the agent to gather and analyze information in order to make a decision and to act on the process. The second ability is the *Know-How-to-Cooperate*, which is the ability to cooperate with another agent to reach a common goal. The Know-How-to-Cooperate allows agents to build a representation of other agents, in order to infer intention, to detect and manage interferences that could appear in their mutual understanding of process. The Know-How-to-

Cooperate also leads to identify criteria for a dynamic task allocation between agents. Know-How and Know-How-to-Cooperate are very useful functions, well-assessed by automation and computer science community as well as by human science community. The discussions with human science researchers may sometimes underline that such a model still appears to be too restrictive to represent all cognitive capacities of human. Nevertheless, they also underline that this model often constitutes a cooperative support between Human Science community and engineers, model then applied as a "common language" between human and machine. This report aims to highlight the usefulness of the model to design new systems, as well as to evaluate new or existing systems thanks to a detailed coding of individual and cooperative activities. Several works are currently in progress in LAMIH to improve Know-How and Know-How-to-Cooperate functions. So far, the model has been mainly tested and adapted in dynamic environments like driving tasks (automobile, aeronautic, railway). The model has been improved in robotics (crisis management, manufacturing systems) with a focus on the identification of levels of automation (*i.e.* role and authority of humans and machines), as well as on the levels of activity linked to organization (low to high decisional levels), and levels of cooperation dealing with task allocation criteria and tools to support cooperation.

Indeed, human and technical agents must be aware of process state, but they also need to be aware of other agent's involvement in the process control. The notion of *Common Work Space* has been defined to reach such needs by providing support for agents' communication, situation awareness and team situation awareness. It was built from workspaces shared between several agents and it gathers different kinds of information from process. However, more than simple shared workspace, we enriched the Common Work Space with information about other agents in order to make explicit their involvement in the process control, and to prevent agents from making too many wrong inferences. The Know-How-to-Cooperate of each agent helps gather agents' information and provide them to the Common Work Space. The enrichment firstly depends on the time agents have to provide information. Secondly, it depends on the ability to extract information from agents in an automatic way. Information about machines' state can be directly extracted, but it is far more difficult to identify human "state". Human monitoring is another topic that must be studied in accordance with human needs if we want to improve human-machine interaction, cooperation and perhaps "complicity".

Therefore, the first chapter having dealt with the Curriculum Vitae, *the second chapter* is dedicated first to the state of the art in Human-Machine Systems (HMS), the identification of the missing points between our objectives concerning Human-Machine cooperation and the current results in research in different disciplines and domains of application. However, such a topic is very wide and we will focus on the main and generic models used for dynamic situations, considering numerous and different types of shared function between human and machine*, i.e.* decisional tasks as well as action ones. The state of the art also provides the analysis of existing models from Automation, as well as Human Science. This analysis leads to the need to define cooperation between a human and a machine; definitions are presented in the chapter 3.

The third chapter details the definition of cooperation on which we based our research, and compares cooperation to other kinds of interactions, such as the levels of automation approach. The study of this definition from an engineering point of view leads to identify the three main key elements to combine in order to propose different levels of cooperation, *i.e.* the *Know-How*, the *Know-How-to-Cooperate* and the *Common Work Space*. The off-line and on-line update of levels of cooperation are also discussed. Nevertheless, the

definition of cooperation between two agents raises the question of cooperation between several humans and several machines, a situation often experienced in the everyday life in both the public and private sphere. The *multi-level aspect of the cooperation* came from this statement. Indeed, humans are, most of the time, organized into several hierarchical and activity levels. The end of the third chapter aims to study and support interactions and cooperation inside and between levels of activity.

The fourth chapter sums up main aspects relevant to cooperation previously presented by the means of a method guiding the design and the evaluation of HMS based on the model of cooperation. The models of cooperation previously presented are implemented in order to propose a formal and generic method to identify suitable levels of cooperation, as well as several kinds of experimental tools to evaluate designed HMS based on these levels.

Chapter 2. Human(s)-Machine(s) System: State of the art

Researchers in System engineering and automation have worked for a long time on the design of systems able to replace or compensate human reliability problems. Researchers and engineers are used to adopting techno-centered design approaches favoring the definition and allocation of tasks to automated systems, only considering human operators at the end of the design process once the control system defined (Trentesaux & Millot, 2016). Such designers assumed that this design approach would identify an *a priori* task allocation, each task being allocated to the best agent (Fitts, 1951) and the HMS's performance was therefore presumed to be optimal. This conception has been questioned in a convincing way by several authors (Bainbridge, 1983; Reason, 1988; Thomas B. Sheridan, 1992; D. D. Woods, 1986). Such a Machine-centered strategy, also called residual strategy due to engineers' behavior to automate whatever they can, is still used by researchers and companies, only allocating task that cannot be automated, *i.e.* the residues, to human operators (Chauvin & Hoc, 2014). New conceptual approaches took shape considering more and more cooperative aspects of human-machine interaction. The Human-Machine system, Human and machine both involved, was the focus of system design (Erik Hollnagel & Woods, 1983), especially with the proposition of "joint cognitive systems" (E. Hollnagel & Woods, 2005). Therefore, several authors proposed other approaches dealing with Human-centered design approaches, such as Human-centered automation (Billings, 1996).

Nevertheless, despite the integration of an increasing number of human and machine characteristics in the design of HMS, an important aspect still lacked, the relevance and the definition of cooperation, until the notion of Human-Machine Cooperation was conceived (Jean-Michel Hoc, 1996; Jean-Michel Hoc, Cacciabue, & Hollnagel, 1995). Indeed, the machine was designed with very limited cooperative features, and the human operator remained responsible for the overall task allocated to the complete HMS. The objective of the Human-Machine Cooperation (HMC) approach is to take into account not only tasks but also functions that can be allocated to human and/or machine according to their individual needs to respond to their common objectives. Coordination tasks needed to be added, to human and machine, in a way that human overload and misunderstanding were avoided, and so in order for human to avoid interacting with "clumsy" automation (D. Woods, 1997).

Therefore, the HMC approach implies the consideration of new operations. In addition to those strictly necessary for task execution by a single agent to control a system, new tasks have to manage role allocation, conflict resolution between goals, and so forth. Organization becomes an important aspect to involve in the design approach. Boy proposed the AUTOS pyramid (Artifact, User, Task, Organization and Situation) to support the life cycle of an HMS from design to decommissioning (Guy A Boy, 2006). The pyramid he designed (cf. Fig. 3) highlights the main points to be taken into consideration when organizing interactions between users and artifacts according to the task to perform for a specific situation. On top of identifying the main actors, the pyramid also underlines the necessary adaptation of the HMS, especially according to the type of situation and the type of task.

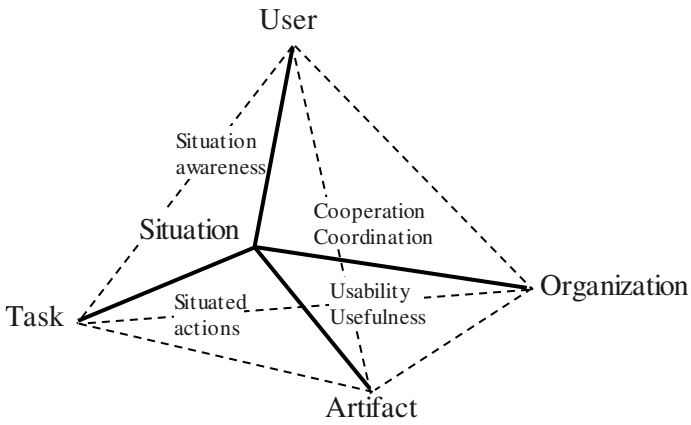

Fig. 3 AUTOS pyramid (Artifact, User, Task, Organization and Situation)(Guy A Boy, 2006)

Parts of the interactions presented on the AUTOS pyramid are described through the user point of view in the next section, while the different types of organization that can be proposed between several humans and artifacts, called assistance systems are described in the section that follows. The last section pays particular attention to the notion of awareness which is crucial not only for the situation but for all the summits of the pyramid.

2.1 Human

Human-Machine System designers are, most of the time, automation or computer science engineers, but since human is part of the system, designers have to be aware of human factors, and even more so, be able to understand and use models provided by cognitive psychology studies. While the activities of a system are usually directly accessible by the examination of the explicit instructions in the program code (even if this access will be less easy in the future with machine learning), such an examination is difficult to conduct with humans. Human cognitive activity has two parts: an explicit part, which is the directly observable overt behavior, and an implicit part, only attainable by interpretation and by determining the behavior structure (Jean Piaget, 1947). Therefore, models may help identify main cognitive functions involved during human activities, but many are hidden and can only be assumed by the designer. Two main aspects of human cognitive activity will now be presented, they tackle the models and characteristics which would be used by designers.

2.1.1 Human information processing

Among the tools and approaches proposed by human-centered design and HMS approaches, the model of human information processing put forwards by Rasmussen and Goodstein in 1987 (Rasmussen & Goodstein, 1987) was used as a basis to identify the human ability to perceive, diagnose and control a process (cf. Fig. 4). In the decisional ladder presented by the authors, all the steps followed by a human are detailed, from the detection of a need of action to implement on the process, to the execution of a formulated procedure. In 1995, Hoc and Amalberti proposed a revised version of the decisional ladder, coming from research on diagnosis, both in experimental psychology and in cognitive engineering, with nine main steps.

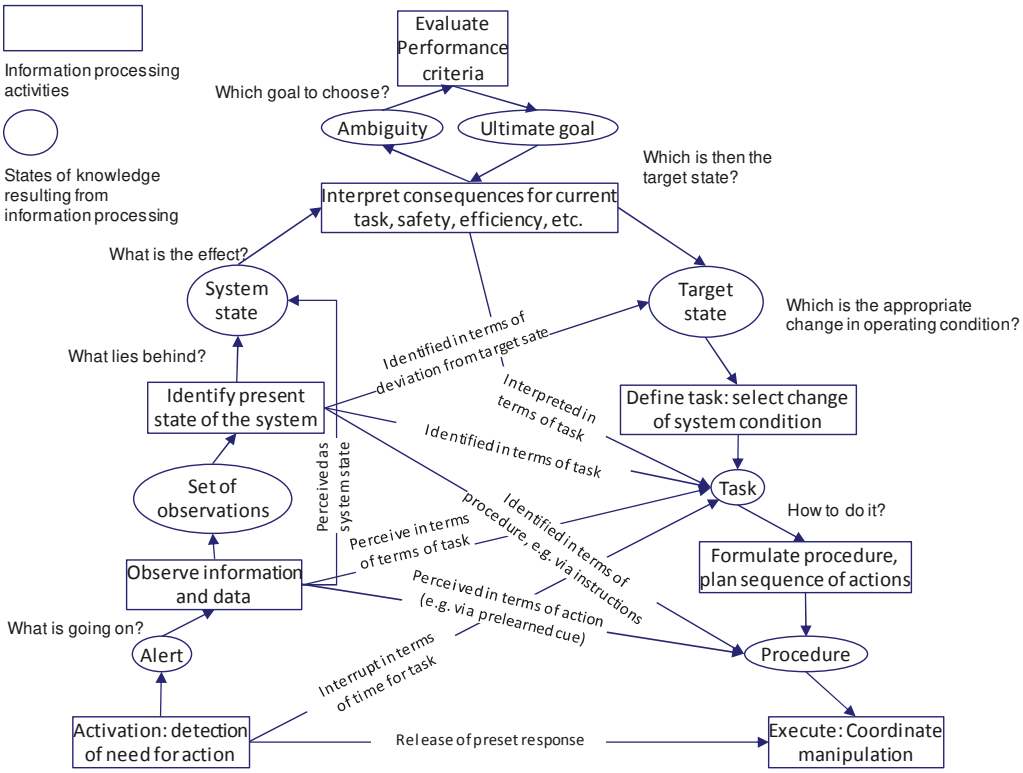

Fig. 4 Schematic map of the sequences of information processes (Rasmussen & Goodstein, 1987)

Intermediate steps might be avoided with shortcut arrows between going up phases and going down phases. The possibility of shortcuts depends on the human's experience and knowledge regarding the situation of the process that they have to manage and the target to be reached. Rasmussen proposed a synthesis of such shortcuts through the KRS-based model (Rasmussen, 1983). The model, presented in Fig. 5, suggests extracting three types of behavior. The more complicated and longer-term loop behavior, called the Knowledge-based behavior (KBB), is used when the process state is unfamiliar to the human and when this human needs to utilize their knowledge to find out a solution. The intermediate behavior, called the Rule-based behavior (RBB), is used when the human has already met similar process problems in the past and had found up global solutions. Rules had been defined that can be applied again on similar situations. The shorter-term loop behavior, called Skill-based behavior (SBB), is no longer a cognitive behavior but a sensorimotor one, close to the automated loops well known by the automation engineers. While KBB and RBB are conscious processes, SBB is a subconscious one.

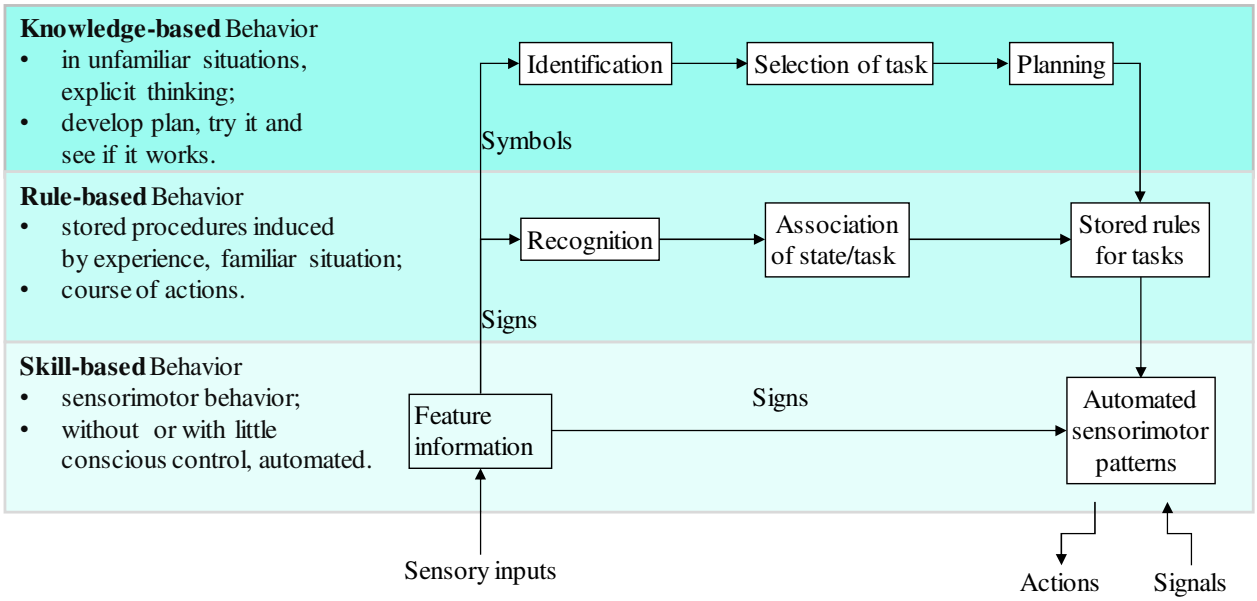

Fig. 5 KRS-based model (Rasmussen, 1983)

Such models (Fig. 4 and Fig. 5) are very useful for automation designers to provide human with assistance systems adapted to each step. The next list presents the nine steps and the several assistance systems that were proposed to support human cognitive activity (Taborin & Millot, 1989). The global steps are:

- *Detection*: assistance systems to keep human process representation and to support process monitoring
- *Explicit search*: assistance system to filter information among and to provide relevant ones regarding the alert
- *Identification*: assistance system to check the certainty of a hypothesis to predict process state
- *Interpretation*: assistance system to infer a hypothesis to anticipate process state
- *Evaluation*: assistance system to test a hypothesis to diagnose process state
- *Task definition*: assistance system to define task to solve process problem
- *Goal definition*: assistance system to define goal to solve process problem
- *Planning*: assistance system to plan goals and tasks identified in the previous steps
- *Execution*: assistance system to implement actions and check that the implementation was successful and had the desired effect to solve process problem

Rasmussen's models support our research in identifying human capabilities according to the type of decision they have to make, and according to their expertise and experience in the tasks to perform. Chapter 3 proposes an extension of these models, for now focusing on the interaction between human and process, to the interaction between human and assistance system.

Humans adapt their behavior according to process state and evolution. Whatever the process, most of the time, it can be considered as a dynamic situation that a human has to supervise and control. The characterization of the type of dynamic situation may help automation designers in the choice of assistance system it would be interesting to provide to the human. These characterizations are now presented.

2.1.2 Cognitive dimensions to control dynamic situations

Hoc proposed five cognitive dimensions influencing humans in the supervision and control of dynamic situations (Jean-Michel Hoc, 2000). These dimensions are the supervisory span, the control directness, the process information accessibility, process speed and are continuity. For each dimension, examples of assistance systems extracted from HMS studies are given in order to mitigate or compensate the negative effect of an excessive value in the dimension (Marie-Pierre Pacaux-Lemoine, Berdal, Enjalbert, & Trentesaux, 2018).

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 ships. A ship needs time to reach the direction or the speed requested 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. In contrast, a large supervisory span may lead to difficulty in identifying process state, to build a model and to make decision at the right time before decision begins to be obsolete. A typical example is fighter aircraft piloting. During certain phases of the flight, a pilot is unable to make a decision due to the high speed of the aircraft and the rapid sequences of actions. All actions must be planned before the mission 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.

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 overly long casual chains, may prevent humans from anticipating what the impact of their actions could be. A process with restricted control is more robust because complications are less likely to arise. Control directness relates then to complicated and dynamic systems. 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 to grasp global process through its sub-parts. The Human-Machine System approach 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 has to make inferences and hypotheses. It could also be a problem of timing. Indeed, a variable can be accessible, but too late, to diagnose process and make decision. In this case, model-based predictions must be made.

The fourth dimension relates to *process speed*. It concerns typically sampling frequency and the time the human has to monitor processes to be sure not to miss an important piece of information. This dimension also deals with the human’s ability to plan during control task if the process is slow, *e.g.* blast furnace, or fast, such

as in highly automated systems. In the first case, simulators provide useful tools to allow a human to build a representation of the process according to a specific time. In the second case, assistance systems like autopilot replace humans' skills and reduce their workload due to time pressure induced by process speed.

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

A human feels 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 needs.

Cognitive dimensions help guide our work regarding the identification of the complexity of processes from the human capabilities point of view, and how assistance systems may support human to mitigate such complexities. Chapter 3 will present the cooperative agent model that supports the design of adaptable assistance systems. Such types of system take into account the dynamic of these dimensions to suit the current and future needs of human in the supervision and the control of the process.

2.2 Human and machine organization

In accordance with the previous section, as soon as automation provides results to be integrated in human decisional processing, automation designers may have to cooperate with Human sciences. Automation and Human sciences have to identify common objectives and share common languages, as well as models. The path to cooperation between researches from different fields is a long one, which the HMS domain has already started. This domain aims to consider Human operator and assistance system in the same way, each one having their own competences and capacities which must be updated if necessary to enable fruitful cooperation. Thomas Sheridan put forwards the first principles of HMS in 1974 (T. Sheridan & Ferrell, 1974). The authors proposed models of human performance related to information, control and decision. Such principles aim to adopt a Human-centered design approach, considering the current and future activity of Humans at the first steps of the HMS design. Human-Machine Cooperation focuses on cooperative goals and aims to take into account objectives, competences and characteristics of each agent, both human and technical, to find the best organization regarding the situation to control. Organization can be defined according to different criteria or objectives. Several have already been suggested and evaluated, and are now presented in the following sections.

2.2.1 Cooperative structures

The first works in cooperation focused on task allocation and authority management. Millot and Mandiau defined the "vertical" and "horizontal" structures of cooperation (cf. Fig. 6)(Patrick Millot & Mandiau, 1995). In the vertical structure, the machine ability is limited and is only able to provide an analysis of the situation and a set of solutions to a human. The human can select one solution and implement it. The machine has no access to the control of the process but cooperates with the human to find the best solution. An example is the

GPS in a car, which provides advice to the driver who, however, is not obliged to follow this advice: the driver alone has control.

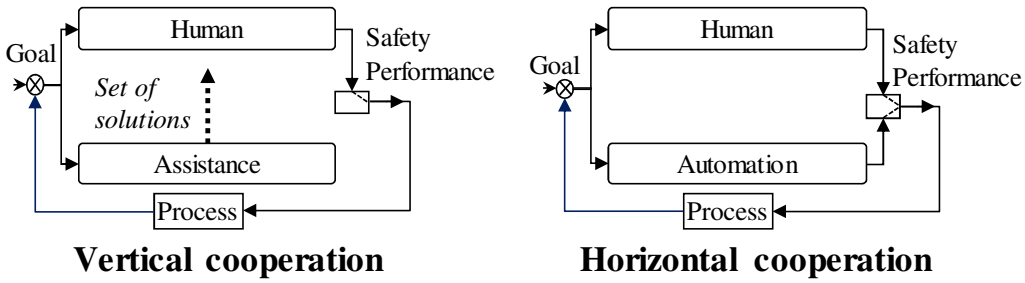

Fig. 6 Cooperative structures adapted from (Patrick Millot & Mandiau, 1995)

In the horizontal structure, both human and machine can fulfill all the tasks of the decisional processing from the analysis of a situation to the implementation of actions. Therefore, structures of cooperation depend on the abilities of each agent to select the best action to solve the problem, but the horizontal structure allows implementation by the automation. Expert systems are typical cases of vertical cooperation. Subsequent sections of this chapter consider both structures as a potential ability to cooperate, but more details about the horizontal one will now be given with a description of the cooperative modes.

2.2.2 Cooperative modes

Rieger and Greenstein (1982) proposed "explicit" and "implicit" modes of cooperation (cf. Fig. 7)(Rieger & Greenstein, 1982). In the explicit mode, automation offers its solution and the human has to choose between their solution and the solution proposed by the automation. In the implicit mode, automation implements its solution directly. The principles of explicit task allocation tested by these authors were very specific to discrete tasks, based on queuing models on one hand or on the information theory on the other hand, and very difficult to implement in concrete worlds. Five years later, Millot showed their feasibility in a theoretical micro-world involving tasks of supervision of independent variables (Patrick Millot, 1988). In 1992, Millot started supervising several PhD theses which experimented both modes of cooperation in the Air Traffic Control domain (F. Vanderhaegen, Crevits, Debernard, & Millot, 1994). The objectives were to manage Air Traffic Controller workload by way of an assistance system able to manage conflicts between two planes. The human controller decides the task allocation in the explicit mode, and automation decides the task allocation in the implicit mode. One of the findings was that the human controller was not confident enough in the automation's decision to abandon the control of task allocation, even if they could be overloaded by task allocation, which is an extra task to fulfill. Moreover, automation solutions were not always the best ones or did not suit human solutions regarding overall traffic (§7.1 provides more details about these experiments).

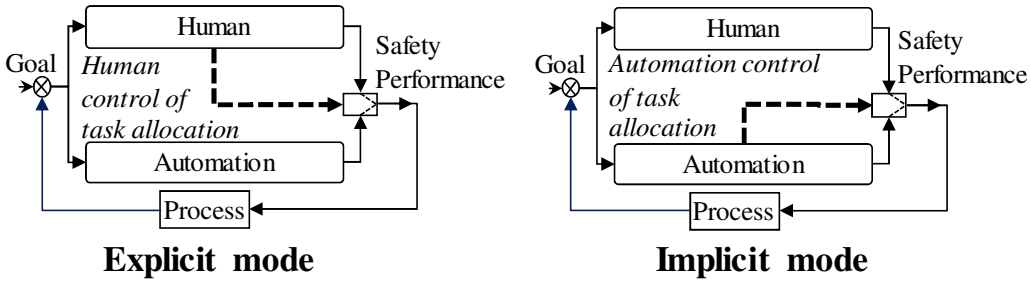

Fig. 7 Cooperative modes (solid lines: commands, dotted lines: information) adapted from (Rieger & Greenstein, 1982) and enriched by (Patrick Millot, 1988)

In order to compensate such difficulties, *i.e.* managing human workload as well as checking usefulness of automation solutions, Lemoine et al. (M.-P. Lemoine, Debernard, Crevits, & Millot, 1996) proposed to experiment a new mode, called the "assisted explicit" mode (cf. Fig. 8). This third mode would allow two types of assistance system to be distinguished. They focus on different goals; one tackles strategic goals when the other tackles tactical goals. The Fig. 8 provides the schema of such an organization. Automation B suggests implementing the solution given by Automation A to Human B who is at an upper decisional level than the one concerned by the control task, *i.e.* Human A. Therefore, Human B decides the allocation. The assisted explicit mode involves more acceptability and less workload induced by cooperative tasks. Indeed, Air Traffic controllers work in pairs, one controller focuses on aircrafts inside a sector (Human A) when a second controller focuses on aircrafts entering and exiting a sector (Human B). The time span to make a decision as well as type of information managed by the second controller allow having a good anticipation of the first controller's workload, solutions and agreement with assistance system's solutions in order to decide task allocation. Moreover, the first controller trusts the second controller because they choose to work together and they have a good model of each other.

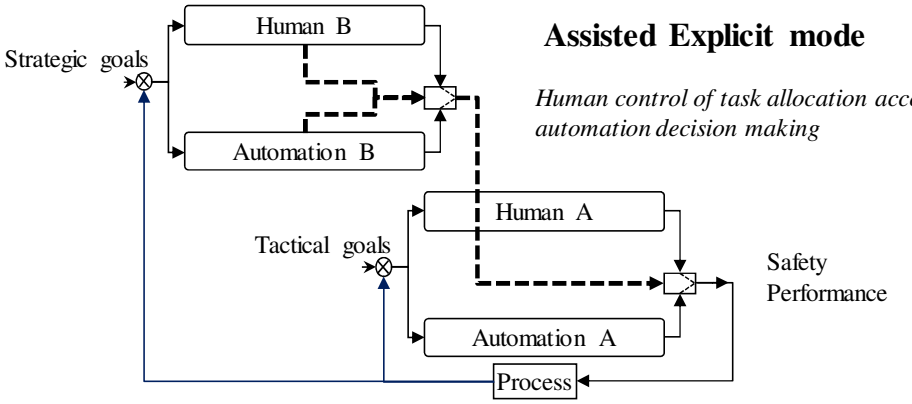

Fig. 8 Assisted explicit mode (solid lines: commands, dotted lines: information) adapted from (M.-P. Lemoine et al., 1996)

A dedicated assistance system supported the second controller to present future traffic, shareable tasks *(i.e.* conflicts that the assistance system can manage) as well as the detection of future controller overload. This assistance system makes the decision to allocate a conflict to the first controller or the automation, but the second controller can modify the decision. Results stemming from experiments conducted on this new mode of cooperation demonstrated the interest, especially regarding acceptability and efficiency. More details about this experiment can be found in §7.1.

Previous sections about structures and modes of cooperation mainly dealt with authority management for task allocation, usually using criteria such as human trust and workload, but that is with a general point of view, without providing possibilities to define shareable tasks in a dynamic way according to situation and the evolution of competences and capacities of human and assistance system. The next section presents forms of cooperation, which are more focusing on complementarity between human and assistance system according to the evolution of such abilities.

2.2.3 Cooperative forms

Schmidt (1991) proposed three forms of cooperation, the "integrative", "augmentative" and "debative" forms of cooperation (cf. Fig. 9)(Schmidt, 1991). The "augmentative" form is the selected form when both the human and the assistance system have similar competences to perform the task. They can share the task in order to adapt the capacity of the overall human-machine system. The "integrative" form is the selected form when human and assistance system have complementary competences. In that case, they can share the task in order to improve the adaptability of the overall human-machine system. The "debative" form is the selected form when human and assistance system have similar competences, but in this form, they can debate the best solution in order to improve the reliability of the overall human-machine system (Thomas B. Sheridan, 1992). Therefore, forms of cooperation deal with the identification of criteria to organize task sharing.

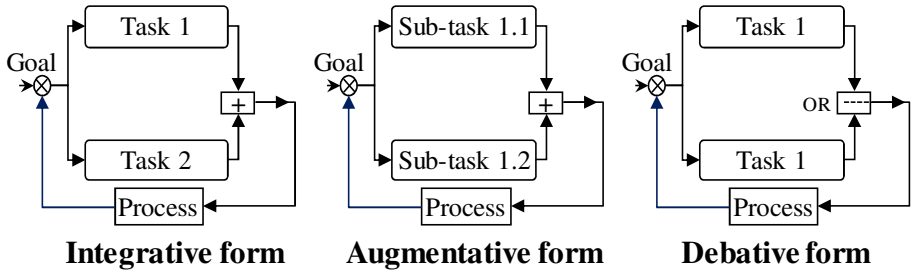

Fig. 9 Cooperative forms adapted from (Schmidt, 1991)

Structures, modes and forms of cooperation provided a basis to analyze and define task allocation, authority management and organization between the human and the machine. Nevertheless, they do not tackle all possible criteria that can influence human-machine system efficiency and acceptability. Other works and approaches proposed new criteria and organizations defining levels of automation and they are presented in the next section.

2.2.4 Levels of automation

Levels of automation or automation modes have been discussed for a long time (Rasmussen, 1981; T. B. Sheridan & Verplank, 1978). Several studies applied them, firstly in aviation (Billings, 1996), and more recently in manufacturing (Lindström & Winroth, 2010), in unmanned aerial vehicles (M L Cummings & Mitchell, 2007) and in nuclear power plants (Jou, Yenn, Lin, Yang, & Chiang, 2009). Indeed, one way to study how human and assistance system can work together consists in knowing detailed competences of each one, before deciding task allocation. Sheridan proposed a machine centered approach by defining firstly five human roles for supervisory control (cf. Fig. 10)(T. B. Sheridan, 1984).

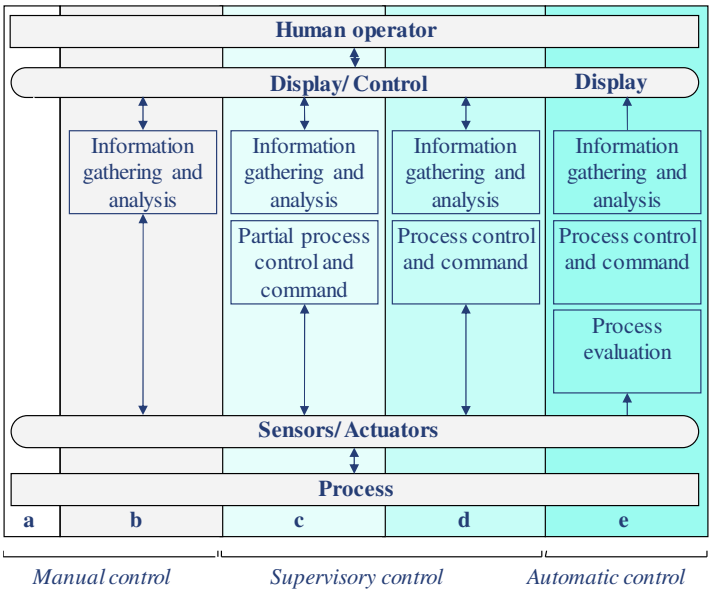

Fig. 10 Supervisory control (T. B. Sheridan, 1984)

He defined then ten levels of automation for decision and control (Thomas B. Sheridan, 1992)(cf. Fig. 11), and ten levels of automation for information acquisition and integration (Toshiyuki Inagaki & Sheridan, 2008).

The computer:

1. Offers no assistance
2. Offers a complete set of decision/action alternatives
3. Narrows the selection down to a few
4. Suggests one alternative
5. Executes that suggestion if the human approves
6. Allows the human a restricted time to veto before automatic execution
7. Executes automatically, then necessarily informs the human
8. Informs the human only if asked
9. Informs the human only if it, the computer, decides to
10. Decides everything, acts autonomously, ignoring the human

Fig. 11 Degrees of automation for decision and control (Thomas B. Sheridan, 1992)

The computer:

1. Offers no assistance
2. Suggests many sources of information, or
3. Narrows the sources to a few, or
4. Guides the human to particular information, and
5. Responds to questions posed in restricted syntax, or
6. Responds to questions posed without restricted syntax, and
7. Integrates the information into a coherent presentation, or
8. Integrates the information into a coherent presentation, with an indication of confidence about each aspects, and
9. Passes it to the human or automation for actions, but allows for other considerations
10. The computer collects information as it sees fit, packages it, and presents it to human or automation for action with no opportunity to consider alternatives

Fig. 12 Levels of automation for data acquisition and integration (Toshiyuki Inagaki & Sheridan, 2008)

Inagaki proposed adding a level 6.5 for decision and control when the assistance system executes automatically after telling the human what it is going to do (T. Inagaki, Moray, & Itoh, 1998). The capability to make a decision would be split into three levels (from 2 to 4): a proposition of a set of decisions/alternatives, a selection of decisions or one selected decision. Regarding the capability to execute a decision, two levels of decision-making would be made (from 5 to 10). The first level is the capability for the assistance system to perform the execution. The second level is the capability for the assistance tool to decide the task allocation. The fourth and last levels differ in terms of communication aspects. To sum up, Sheridan organized the ten levels according to the precision of the decision-making, the capability to decide allocation and the capability to communicate to human.

Kaber and Endsley offereed another taxonomy of levels of automation, implementing a more human-centered approach. Ten levels were also proposed but according to four types of activity: Monitoring, Generating, Selecting and Implementing (Endsley & Kaber, 1999; Kaber & Endsley, 2004)(cf. Fig. 13). The authors described activities as roles allocated to human or to assistance system, or both. Monitoring includes information gathering to perceive process status. Generating allows for the formulating of task strategies to achieve goals. Selecting leads to choosing a particular strategy. Implementing carries out the chosen strategy.

	Monitoring	Generating	Selecting	Implementing
(1) Manual control	H	H	H	H
(2) Action support	H/M	H	H	H/M
(3) Batch processing	H/M	H	H	M
(4) Shared control	H/M	H/M	H	H/M
(5) Decision support	H/M	H/M	H	M
(6) Blended decision making	H/M	H/M	H/M	M
(7) Rigid system	H/M	M	H	M
(8) Automated decision making	H/M	H/M	M	M
(9) Supervisory control	H/M	M	M	M
(10) Full automation	M	M	M	M

Fig. 13 Levels of automation (Endsley & Kaber, 1999)

Parasuraman et al. proposed similar approach by defining automation at four stages (Parasuraman, Sheridan, & Wickens, 2000). Assistance systems can support a human at four main stages (cf. Fig. 14):

- Acquisition of multiple sources of information, including sensory processing, preprocessing of data, and selective attention.
- Manipulation of information in working memory and cognitive operations such as integration, diagnosis, and inference, occurring prior to the point of decision.
- Decisions based on such cognitive processing.
- Entailment of an action consistent with the decision choice.

Percentage of allocation to automation between low and high involvement defines task sharing between human and machine. In Fig. 14, system A is highly automated and system C designed with little automation.

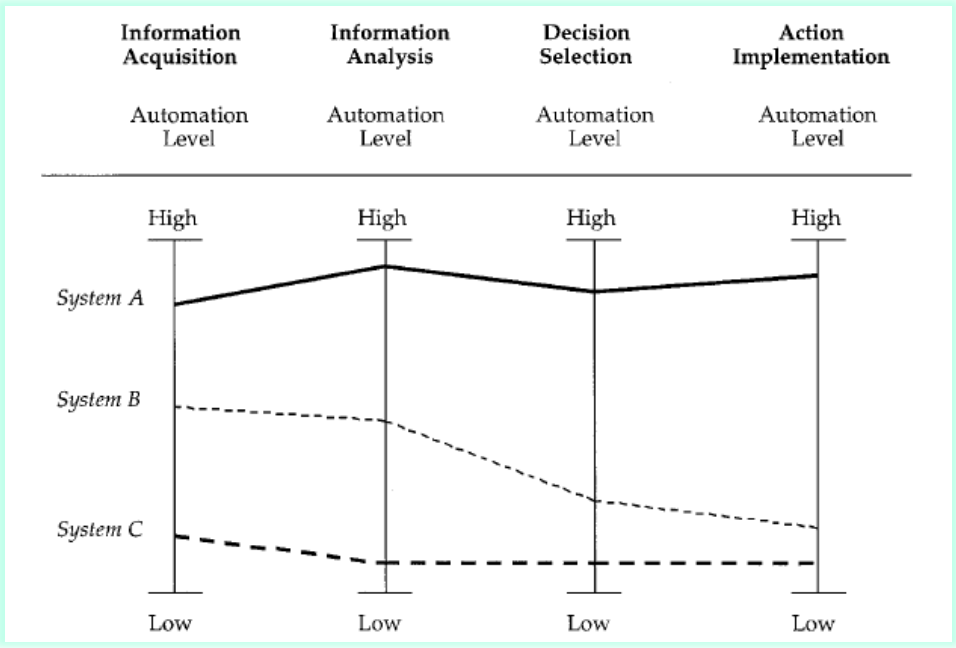

Fig. 14 Types and levels of human interaction with automation (Parasuraman et al., 2000).

With a similar objective of finding the best task sharing between human and automation, Flemisch et al. proposed the H-mode, based on the H(orse)-Metaphor (F. O. Flemisch et al., 2003). The metaphor aims to characterize the roles of human and automation as similar to the roles of a rider and a horse respectively. Mainly applied in the automotive domain, the H-mode describes the haptic-multimodal interaction and execution of the driving task by the human and the automation.

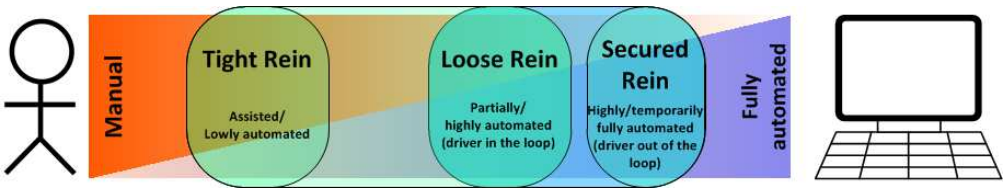

Fig. 15 Cooperative Guidance & Control with H-Mode (Altendorf et al., 2016)

Table 3 gives a synthesis of the above definitions, mixing the approaches proposed by Sheridan & Inagaki and by Kaber & Endlsey, by integrating progressively more capability of the assistance system and by taking into account types of activity. Criteria were also formalized to distinguish levels for which an assistance system is able to carry out a solution and/or to decide an allocation. Explicit allocation differs from implicit allocation by whether the human confirms or not the allocation respectively. Moreover, there are three kinds of time constraints to decide allocation. The first one used by the level 5 is "t_c". It refers to the assistance system's capability to control allocation ("c" for control). If the human consents to allocate the implementation of action to the assistance system responding to its question, t_c is different from zero and implementation is automated. This value is also used by the level 6 but with the goal of comparing it to a time limit. If the human does not veto the allocation of decision and/or action, the assistance system completes the task. The other defined times are "t_i" and "t_a". They are respectively the time to provide or to require information ("i" for information) to the other, and the time to perform the action ("a" for action). Levels from 6.5 to 9 are different according to these times. The assistance system performs the task before or after giving feedback.

Communication between the human and the assistance system only deals with feedback about automated implementation. The feedback is implicit when the assistance system always provides feedback about its decision and action. It is explicit when it is on human demand. It is an assessed feedback when the assistance system assesses the necessity to provide the feedback to the human. Contrary to the degrees defined by Sheridan, Kaber and Endsley do not discuss in terms of elapsed time to decide allocation or to give feedback. They focus on the need for the human to validate the allocation. Moreover, the allocation does not relate to action but also to diagnosis and decision making.

The representation of levels of automation given in Table 1 underlines what would be a sharing of the role according to the type of capability human and assistance tool have. A look at this table (from level 2 until 9) shows that both agents need to gather information. However, information acquisition can be different between the two agents, especially if the human and the assistance tool have not the same access to process information. To sum up, Table 1 underlines the task to allocate to the human, to the assistance tool or both. When only one agent can perform a task, it is a predefined task allocation. When two agents can perform a task, criteria must support the selection of one or the split of the task into subtasks in order to share the load.

Know-how — Example of Shareable task — Example of Communication — Rules to allocate task — Rules + Communication

	Levels of automation	*Criteria of task allocation*	*Information acquisition*	*Information analysis*	*Decision and action selection*	*Action implementation*
1-(1)	No assistance		H	H	H	H
2	Set of decisions		H/M	M	H	H
3	Selection of a few decisions		H/M	M	H	H
4	Selection of one decision		H/M	M	H	H
(2)	Action support		H/M	H	H	H & M
(3)	Batch Processing	Explicit allocation of action	H/M	H	H	M
(4)	Sharing control	Explicit allocation of action	H/M	H & M	H	H & M
(5)	Decision support	Explicit allocation of action	H/M	H & M	H	M
5	Carrying out of one solution	if $t_c(H) \neq 0$	H/M	M	H	H/M
(6)	Blended decision making	Explicit allocation for each stage	H/M	H & M	H or M	M
6	Carrying out of one solution	if $t_c(H) < t_{limit}$	H/M	M	H/M	H/M
(7)	Rigid system	Explicit allocation of action	H/M	M	H	M
(8)	Automated decision making	Implicit allocation for each stage	H/M	M & H	M	M
(9)	Supervisory control	Implicit allocation for each stage	H/M	M or H	M	M
6.5	Carrying out of one solution	$t_i(M) < t_a(M)$	H/M	M	M	M
7	Carrying out of one solution	$t_i(M) > t_a(M)$, implicit feedback	H/M	M	M	M
8	Carrying out of one solution	$t_i(M) > t_a(M)$, explicit feedback	H/M	M	M	M
9	Carrying out of one solution	$t_i(M) > t_a(M)$, assessed feedback	H/M	M	M	M
10-(10)	Full automation		M	M	M	M

Table 3 Comparisons of automation scales (Pacaux et al., 2011)

Table 3 also underlines some shortcomings. For example, the four stages proposed by Parasuraman may help design the functions according to a different combination. Indeed, the combination may be constructed with a sharing or a trading of control (T. B. Sheridan, 2002), and when functions are shared, the combination may be constructed according to the 3 forms of cooperation which define a basis (Grislin-Le Strugeon & Millot, 1999).

Application domains like the automotive and railway industries have already defined their own levels according to their own needs. The Society of Automotive Engineers has 5 levels of automation, while the NHTSA (National Highway Traffic Safety Administration) has 4 levels (SAE, 2013), and the railway industry has 4 Grades of Automation (GoA) (Cappaert-Blondelle, 2012). Studies dealing with such definitions are detailed in §7.2 and §7.7 respectively, but they also highlighted the need to improve how levels of automation are characterized. Human-Machine Cooperation framework can tackle such issues, with even more information, especially regarding the ability to integrate more information about other agents involved in the same process to control. The next section presents parallel approaches, usually conducted in different fields, such as Computer Science, robotics and aviation, and dealing with levels of autonomy.

This study leads us to question the interest in defining precise levels of automation when most of the time designers have to define levels to suit to their problematics. Chapter 0 proposes following another path to find the best adaptation between human and assistance system, according to more criteria than just time, feedback or decision making of function allocation. Criteria might also be extracted from human, assistance system and process states. Such a reconsideration of levels of automation has also recently been highlighted by Thomas Sheridan and Toshiyuki Inagaki, two of the main authors dealing with these topics (Toshiyuki Inagaki & Sheridan, 2018).

2.2.5 Levels of autonomy

With the increase of machine abilities, especially regarding the function of decision making and authority management, new scales have been proposed and these concern levels of autonomy. Authors defined these levels according to specific functions and objectives to reach. Examples can be found in robotics (Cosenzo et al., 2010a; Prewett, Johnson, Saboe, Elliott, & Coovert, 2010; D. D. Woods, Tittle, Feil, & Roesler, 2004), in industry (Skjerve & Skraaning, 2004) and in aeronautics (Krobusek, Boys, & Palko, 1988). In robotics, for example, Goodrich et al. proposed 5 levels (fully autonomous, autonomous with goal biases, waypoint methods, intelligent teleoperation, and dormant) (Goodrich, Olsen, Crandall, & Palmer, 2001).

Regarding difference between automation and autonomy, some clarifications have been recently provided by the Joint Air Power Competence Centre. This is a team of multinational experts who provide key decision-makers effective solutions on Air and Space Power challenges, in order to safeguard NATO and the Nations' interests. They worked on the definitions and distinctions of automation, autonomy and autonomicity (Haider & Catarrasi, 2016). They argued that: — "an automated system follows a pre-defined and finite thus predictable sequence of actions according to initial or continued human authorization"; — "an autonomous system independently decides its own courses of action to achieve its given objective without human intervention"; — "an autonomic system selects from a pre-defined and finite set of actions to achieve its given objective without supervision unless a human intervenes". Therefore, autonomous systems are less predictable than automated systems, as well as being more independent from humans, and so might be more competent since they able to complete several combined functions, though they are less adapted to human activities. Therefore, it would be interesting to find an intermediate design with the advantages and without the disadvantages of both. Chapter 4 partly uses studies conducted on levels of autonomy to propose a method to

identify appropriate levels of automation for a specific application, especially regarding their adaptability according to several criteria.

However, studies about levels of autonomy are also interesting as they deal with higher decisional levels and complex organization with several humans and machines than the ones usually considered by automation. Fig. 16 provides an example presenting the roadmap developped by the Department of Defense of the United States to design Unmanned Aerial vehicles.

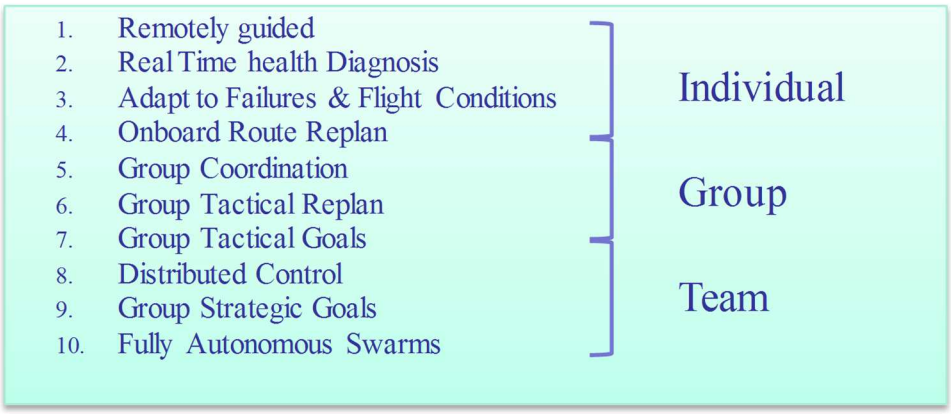

Fig. 16 Autonomous Control Levels (Adapted from the Roadmap proposed by the Department of Defense of the United States to design Unmanned Aerial vehicles (Galster et al., 2007))

The proposed levels took into account three levels of activity, the operational level for individuals, the tactical level for groups and the strategic level for teams. Such an extension of the levels of automation/autonomy will also be discussed in chapter 4 with the definition of the multilevel aspect of cooperation, as well as with the layers of cooperation.

Levels of autonomy and autonomous systems are being cited more and more frequently in current projects, in particular with the expansion of works involving "artificial intelligence". Autonomous systems are able to make decisions and have the authority to implement their solutions. In the future, they might also be able to learn and modify their algorithms. The unpredictability and the difficulty for humans to understand autonomous systems has already been underlined more than 20 years ago with an article about "Automation surprises" (Sarter, Woods, & Billings, 1997). As such problems have not been resolved yet, new ability like learning, will again increase the number of human surprises. Nevertheless, some tools already supported system designers to prevent such surprises, among them the notion of awareness, which is presented in the next section.

2.3 Awareness

The more the number of agents involved in the control of a process or an environment increases and the more agents delegate part of their functions or tasks to other agents, the less they are aware of the process states and other agents' state and involvement. Awareness quickly appears as a central objective in the design of human-machine systems. Literature underlines different aspects of awareness. It may deal with the situation of the process/environment, but also with the situation of the team involved in the control and especially the management of roles and authority within this team. These aspects are described in the following sections.

2.3.1 Situation awareness

Situation awareness (SA) "is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1995b). For the author, SA is the product of mental mechanisms of perception and information processing based on a three-level model:

- SA level 1 is about the perception of the status, attributes, and dynamics of relevant elements in the environment,
- SA level 2 is about the comprehension of a situation, being aware of such elements to include an understanding of their significance in light of pertinent operator goals, and
- SA level 3 is about the projection of the future status of such elements in the environment.

This model remains the most popular as it is the most understandable and close to Rasmussen's problem solving functional model presented in a previous section (Patrick Millot, 2015). The model depicts SA as a component of information processing that follows perception and leads to decision making and action execution (cf. Fig. 17). Mental models (formed by training and experience) are used to facilitate the achievement of SA levels and the development of their maintenance. The very complete paper by Salmon et al. (2007) describes the numerous attempts for defining SA, the authors state that Endsley's framework remains the most commonly used.

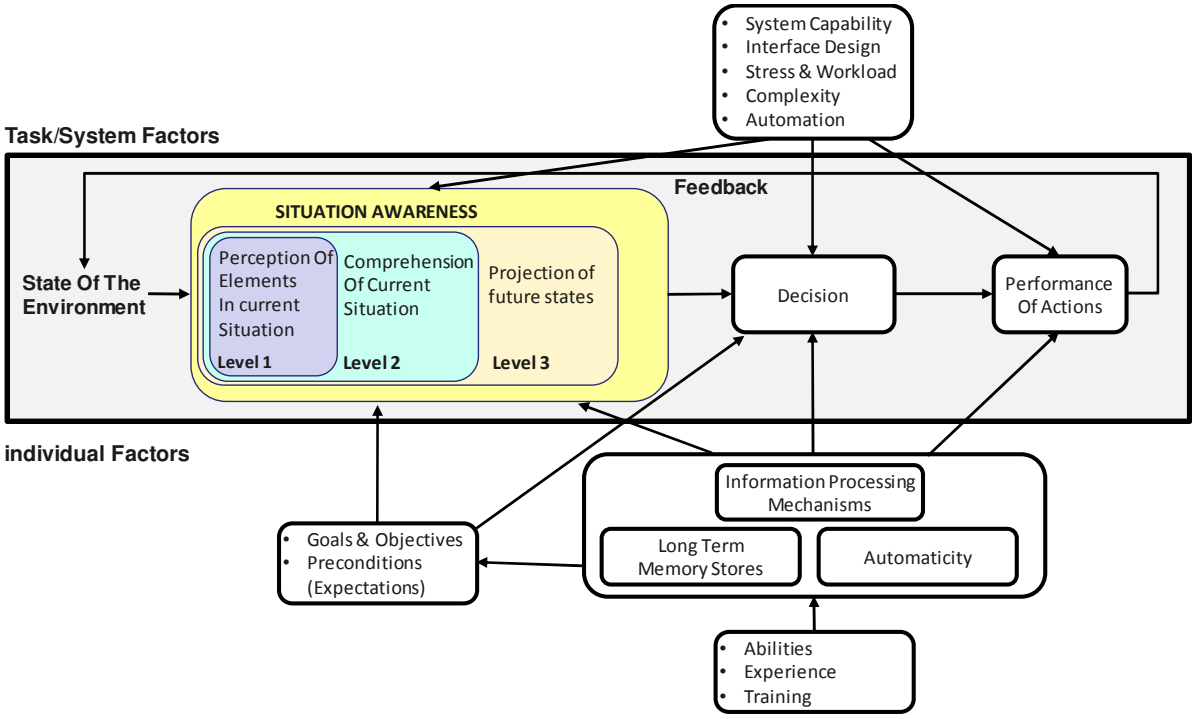

Fig. 17 SA three-level model adapted from (Endsley, 1995b)

In complement to description of individual SA, Salmon et al. (2007) also emphasize the interest of Team SA.

2.3.2 Team situation awareness

They found extensions of the SA studies to groups of decision makers and to collective works. Several researchers have developed frameworks to understand and describe how Situation Awareness can be managed collectively in a group of humans and artificial agents (Salas, Prince, Baker, & Shrestha, 1995; Salmon et al., 2007; Shu & Furuta, 2005). This research topic is still in progress; several studies have been carried out in several application domains like car driving and very distributed situations involving several agents such as road traffic, troop deployment or air traffic. New theories are proposed and tested in order to fix this complicated problem. That results in a great interest for SA and especially the collective SA, in order to evaluate and maintain the human SA level through an adequate adaptive and cooperative automation. The term collective SA described the different meanings proposed in the literature and related to the SA acquired by several people and/or artificial cognitive systems:

- Team SA : Salas *et al.* suggested "a shared understanding of a situation among team members at one point in time" (Salas et al., 1995); Endsley (1995a) conceives team SA "whereby each team member has a specific set of SA elements about which he or she is concerned, as determined by each member's responsibilities within the team". Shu and Furuta (2005), on the base of Endsley's model, proposed a combination of both individual SA and mutual beliefs, as well as a Team SA inference method to evaluate dynamically the impact of new types of interfaces or support systems.
- Shared SA: according to Endsley and Robertson (2000) it refers to "the same SA across shared requirements". Bolstad and Endsley (2000) propose a model of Team SA based on four components:
    - Shared SA Requirements as "the degree to which the team members know which information needs to be shared",
    - Shared SA Devices as "the devices available for sharing this information",
    - Shared SA Mechanisms as "the degree to which team members possess mechanisms" to be able to interpret information,
    - Shared SA Processes as "the degree to which team members engage in effective processes for sharing SA information … checking each other for conflicting information or perceptions, setting up coordination and prioritization of tasks, and establishing contingency planning among others". Salmon et al. (2007) defines Team SA as a combination of individual team member SA, shared SA and the combined SA of the whole team (cf. Fig. 18).
- Distributed SA: Stanton et al. (2006) suggested following set of tenets:
    - SA is held by human and non-human agents,
    - Different agents have different views on the same scene,
    - Whether or not one agent's SA overlaps with that of another depends on their respective goals,
    - Communication between agents may be non-verbal behavior, customs, and practice,
    - SA holds loosely coupled systems together,
    - One agent may compensate for degradation in SA in another agent. Therefore, each agent has an important role in the development and maintenance of other agents' SA.

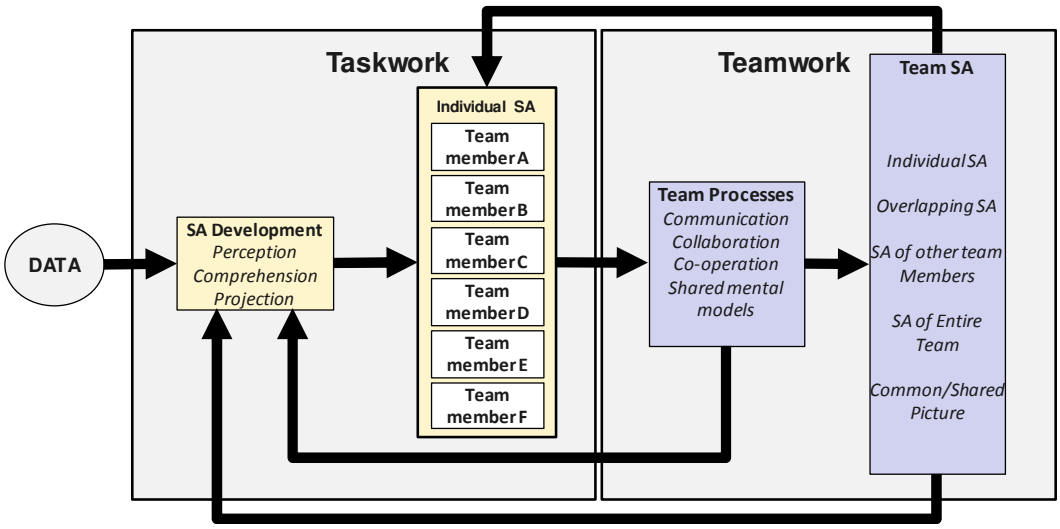

Fig. 18 Team Situation Awareness (Salmon et al., 2007)

Salmon et al. (2007) deduce that teams need to share pertinent data at the higher levels of SA, such as the significance of SA, elements to the team goals and projected states. The team performance will thus depend on the shared goals, the interdependence of team member actions and on the division of labor between team members. Fig. 18 details such interdependence between individual and team SA, based on taskwork and teamwork (Morgan, Glickman, Woodard, Blaiwes, & Salas, 1986). The lack of convergence on team-SA definition seems to reflect a lack of agreement on the foundations to model the phenomenon. Nevertheless the construct of team process seems very close to the framework developed on human-machine cooperation (P. Millot & Pacaux-Lemoine, 2014).

Mode is another word sometimes used to deal with level (Baker & Yanco, 2004a). As explained in the sections about level of automation/autonomy, the selection of one level or mode predefines the roles allocated to human and machine. The fact that human is aware of the role of each one, and in particular what the machine is intended to do, was defined as the mode awareness (Sarter & Woods, 1995; Sarter et al., 1997; Vakil, Hansman, Midkiff, & Vaneck, 1995). These authors mainly focused on the mode awareness problems since, in the example of aviation, pilots may not be aware of the engaged mode.

Situation Awareness studies support our research regarding the use of other criteria to define levels of automation. As an extension of the studies dealing with mode awareness, it seems obvious that all agents involved in cooperative activities to control a process or an environment must be aware of the role of each one. Chapter 4 will describe how we can support awareness, whether to be informed and to understand the process situation, or the agents' state and objectives, or the cooperation between these agents. We called such a support a Common Work Space.

SYNTHESIS ON THE STATE OF THE ART

The present second chapter presented the key elements that must be part of the design of good cooperation between human and machine (cf. Fig. 19). Models representing humans may provide information about humans depending on the complexity of situation and task to complete. Machine can then integrate such information to adapt itself to human needs in an explicit or an implicit way. Models of organization underline how rich the interaction can be, but at the same time, how complex this interaction could also be if designers do not take precautions. One of precautions is to support general awareness. Therefore, competences and capacities of agents to control process and to be aware of other agents involved in this control must be the bases of the design of human-machine systems. The combination of these bases may organize the human-machine system in a way that it is more reliable and adaptable to the dynamic of process due to new events and changes in agents' state. The Human-Machine Cooperation framework aims to reach this goal by analyzing and integrating parts or all elements of models previously presented, and by proposing a generic model of agents. The chapter 3 presents this model and Human-Machine Cooperation principles.

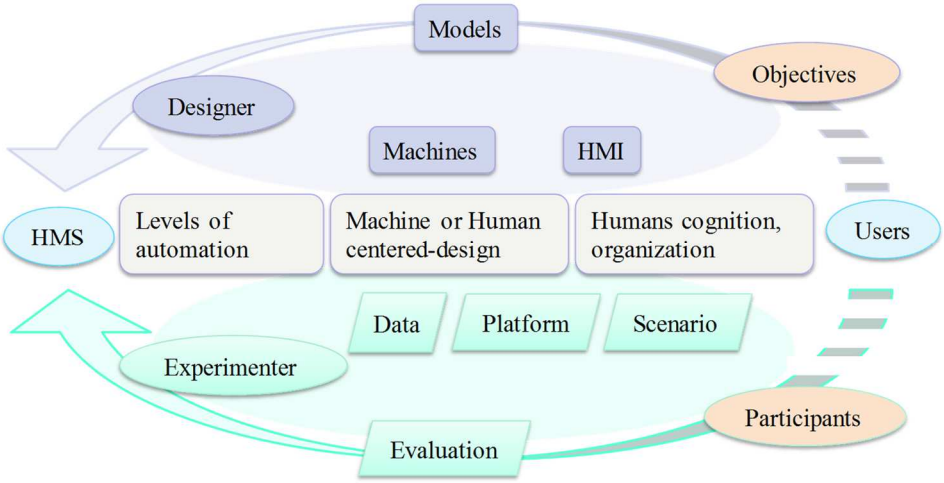

Fig. 19 Synthesis on the state of the art

Chapter 3. Towards Human-Machine Cooperation

Every word or concept, clear as it may seem to be, has only a limited range of applicability, *W. Heisenberg, Physics and Philosophy, 1958*

As far as the laws of mathematics refer to reality, they are not certain, and as far as they are certain, they do not refer to reality. 'Geometry and Experience', an expanded form of an address *by Albert Einstein to the Prussian Academy of Sciences in Berlin, 27 January 1921*

The further we penetrate into the submicroscopic world, the more we shall realize how the modern physicist, like the Eastern mystic, has come to see the world as a system of inseparable and ever-moving components. *Fritjof Capra, The Tao of Physics, 1975*

"A map is not the territory" (1933). *Alfred Korzybski, Science and Sanity: An Introduction to Non-Aristotelian Systems and General Semantics*

1 + 1 = 3 (at least, I hope with all my heart), The Encyclopedia of Absolute and Relative Knowledge, Edmond Wells, *The Revolution of the Ants, Bernard Werber, 1996*

The principles of Human-Machine Cooperation (HMC) have been laid down with a focus on Dynamic Task Allocation (Patrick Millot, 1988; Patrick Millot & Kamoun, 1988). Several domains were particularly adapted to apply these principles, with the objective of sharing or trading functions between human and machine, including air traffic control, fighting aircraft, car driving, robotics, manufacturing as well as the railway industry. Studies conducted through the HMC approach aim to evaluate the risk for Human-machine system to reach an unstable and unrecoverable state. Such a goal can be achieved by proposing a model of cooperation and a method of application in order to assess current or future Human-machine interactions. Indeed, risk could arise from the environment or from an inappropriate behavior of humans or machines regarding a situation. The next section details the model a cooperative agent. The model has evolved, since the late 1990s, when we used it for the first time during the study in air traffic control, until today in manufacturing and the railway industry. The fact is that machines offer more and more abilities to control process and situations, but interaction with human and combination of these new abilities with humans' abilities, are most of the time forgotten. The model of cooperative interaction then presents how to identify and test potential combinations of function. The following sections detail the types of ability to combine, *i.e.* sub-functions of "*Know-How*" and "*Know-How-to-Cooperate*" which will be defined, and the definition of a space able to support cooperation through efficient communication tools, called the "*Common Work Space*". The last section deals with the extension of the principles of HMC to more complex socio-technical systems with the definition of the layers of cooperation.

3.1 Definition of cooperation

All the work I did on cooperation began with many discussions, system designs, experiments and analysis conducted with Jean-Michel Hoc, researcher in psychology in LAMIH, Patrick Millot and Serge Debernard, professors in LAMIH. Hoc proposed the next definition inspired by (J. Piaget, 1977): "Human and machine are in a situation of cooperation if: (a) each of them strives towards goals although interfering with the goals of the other (at least based on resources or procedures), and (b) they try to manage such interference to make easier the activities of the other" (Jean-Michel Hoc, 1996; Patrick Millot & Hoc, 1997). In the definition the term "interference" is borrowed from physics in a metaphoric way and its connotation is not purely negative (signals in phase opposition), but also includes a positive aspect (signals in phase). The definition of cooperation echoes the definition of team proposed by Salas *et al.* as: "distinguishable set of two or more people who interact dynamically, interdependently, and adaptively toward a common and valued goal/object/mission, who have each been assigned specific roles or functions to perform, and who have a limited life span of membership" (Salas et al., 1995). Based on the definition of cooperation, we proposed a model of cooperative agents, humans and/or machines, agents that share a common goal and have to manage interferences to adjust their decisions and actions.

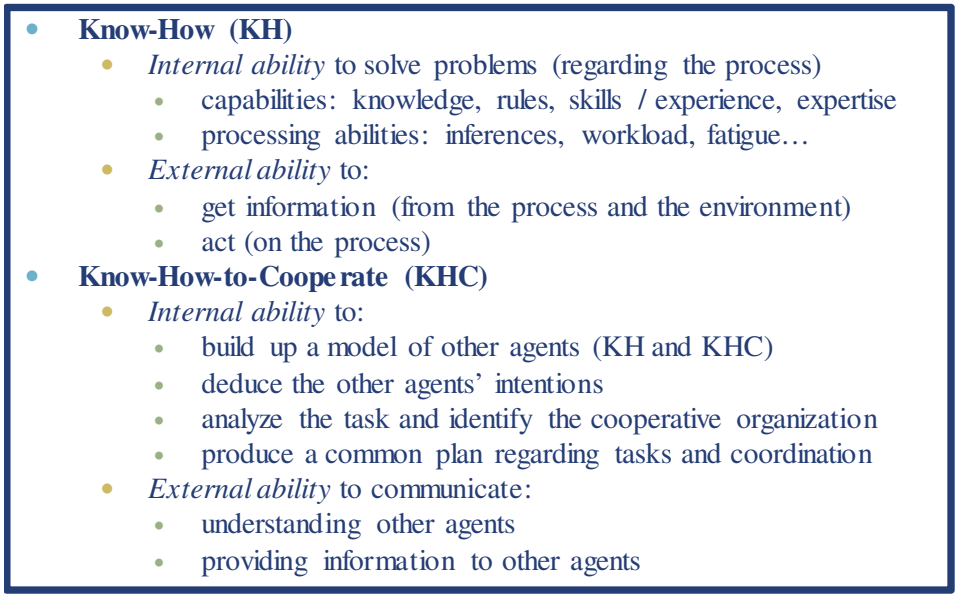

Fig. 20 Model of cooperative agent adapted from (Patrick Millot & Pacaux-Lemoine, 2013)

Therefore, Human-Machine Cooperation studies lead to a definition of the model of an agent based on two dimensions: — the agent's ability to control a process or an environment, also called the "Know-How", and — the agent's ability to cooperate with other agents concerned by the same process or environment, also called the "Know-How-to-Cooperate" (Patrick Millot & Lemoine, 1998). Fig. 20 proposes a synthesis of cooperation attributes, as presented in its last version.

Human cognitive process merges both types of abilities, and it is usually the case during the design of assistance system. Nevertheless, it is interesting to clarify the distinction by highlighting all the types of interactions between agents in order to avoid the recurrent problem of cooperation.

3.2 Towards a meta-model of cooperation

A meta-model of cooperation may support the design and the evaluation of Human-Machine System, especially regarding cooperative aspects. The cooperative agent model is the basis of the meta-model. It specifies and justifies the definition of the three main entities, the "*Know-How*", the "*Know-How-to-Cooperate*" and the "*Common Work Space*" now presented. A generic model of cooperative agents' interactions then offers a schematic representation of cooperation as the result of the complementarity of these three entities. They were defined during my PhD when we had to design cooperative systems to support air traffic controllers' activities when they had to tackle an increase in traffic (Jean-Michel Hoc & Lemoine, 1998a; M. P. Lemoine, 1998) (cf. Appendix 1 - 7.1).

3.2.1 The "Know-How" or the abilities to control the process (KH)

The *Know-How* (KH) of an agent focuses the control of a process or an environment, and not the interaction with other agents. A process is composed of a set of passive and active elements. Passive elements refer to infrastructure, simple mechanisms, and basic objects, *i.e.* elements with no ability to decide and act. Active elements are more or less complex systems, like complicated mechanisms, but there are systems with which an agent considers that is not possible to cooperate; the agent must take it as it is, like the traffic in the case of

transport systems, hostile environment in case of robotics application. In the case of air traffic control, air traffic is the process since we did not consider the cooperation between air traffic controllers and aircraft pilots in our study. Therefore, we consider that the process is not seen as "intelligent" (no decision or action made by the process), but human and technical agents may control it in a cooperative and intelligent way. It is important to define a process in order to be able then to identify who or what is a cooperative agent. In the next parts of the document, we will use the term process, if it is an operative part like in manufacturing or an environment in which vehicle and robots act.

The KH is split up into two parts, one is called the internal KH and the other the external KH (Patrick Millot & Pacaux-Lemoine, 2013). *The internal KH* relates agents' problem-solving processing, *i.e.* their competences and capacity to control a process. Section §2.1 provided a description of competence and behavior of humans, based on knowledge, rules and skills they gained to control the process, according to their expertise and experience (*i.e.* practices) (Rasmussen, 1983). Expertise relates knowledge and rules, when experience is more skill based and improved by training. The more complex a process is, the more an agent needs competence (or procedure) to control it. The more complicated a process is, the more an agent needs training and practice to control it. Complication relates more to the capacity of the agent. The capacity of an agent deals with the number of tasks the agent can perform in a period. It also addresses the endurance of the agent over a long period of time. Competence and capacity affect each other, such as in the definition of acceptable performance, which could be a function of efficiency and cost, with efficiency focusing on competence and cost on capacity (Patrick Millot & Pacaux-Lemoine, 2013). In our air traffic control study, the internal KH of the assistance systems we designed consisted in detecting and solving the simpler conflicts between aircrafts.

The *external KH* is the ability to access the process information and the ability to act on this process. The external KH especially concerns communication aspects. In our air traffic control study, the external KH of the assistance systems we proposed relates their ability to gather information about traffic and to send command to pilots through air-ground data-link communication. Ergonomics rules provide advice to design interface with visible, readable and comprehensible data. The amount of data must be limited and updated in a controlled way, especially when the dynamic of a process is high (cf. 2.1.2). Nevertheless, we will not focus on such ergonomics aspects even if it is very important in the design of tools to support cooperation. The present work is more focusing on the identification of type of data, functions and sub-functions that can be shared or traded between agents.

The KH of technical agents is "normally" more obvious to extract, especially by having access to its code with the help of their designers. However, the fact is that technical agents can learn and define their own rules and knowledge more and more. The perspectives section will discuss this risky machine evolution from the cooperation point of view. That is why we would now like to specify the distinction between the three terms "automatic", "automated" and "autonomous". The term "automatic" usually refers to system with very simple, mechanical responses to environmental input. The term "automated" usually refers to more complex, rule-based systems; while the term "autonomous" refers self-direction and self-learning systems that can have emergent behavior not predictable from its code. The current research deals with systems, which can be self-directed, but not self-learning.

Unlike technical agents, human agents' KH is usually estimated from assessments done before and during work by peers or hierarchy (based on prescribed tasks), but also by the agents themselves. Indeed, human agents build models of themselves thanks to their education, practices and experiences. Self-confidence and trust may depend on their own model. Human agents have to be aware of their competences and capacities regarding the task they have to complete. If they have no confidence in themselves to perform a particular task, they might prefer to cooperate with others and they will ask for help (Goodrich et al., 2001).

Therefore, the internal KH allows agents to build up a representation of the current situation of the process, using their competences and capacities, in order to gather information, to analyze the situation, to make a decision and to implement an action as proposed by (Parasuraman et al., 2000) and presented in §2.2.4. Agents are able to complete these cognitive activities because they interact with process through their external KH. Internal and external KH allow agents to be aware of process state or situation in order to know the current state of the process, to diagnose such a state and to project future states, *i.e.* the situation awareness presented in §2.3.1. However, because of a lack of competence or a lack of capacity, agents may require the assistance of another agent. In this case, they need another ability, namely the ability to take into account the abilities of other agents and to communicate with them. This specific ability is the Know-How-to-Cooperate. In the air traffic control study, the competence of air traffic controllers was fortunately not in question, but the objective was to share air traffic control with assistance systems in order to manage their workload in case of high number of aircrafts. This was an augmented form of cooperation (cf. §2.2.3).

3.2.2 The "Know-How-to-Cooperate" or the agent's ability to cooperate (KHC)

The *Know-How-to-Cooperate* (KHC) allows one agent to take advantage of the complementary KH of other agents. The KHC also has two parts, an external and an internal part. The *internal KHC* allows agent to build up a model, or at least a representation, of other agents in order to make easier the cooperation with them. This model allows them to be aware of the other actors' concerns, expectations and intentions (Schmidt, 2002). Working, training, interact with others enables the development of such a model. Agents progressively identified, memorized and used KH and KHC of other agents in order to achieve cooperative behavior. In the air traffic study, air traffic controllers already had a KHC regarding their mutual cooperation because they were used to working together and they had procedures they had learned during their training; but they had to build a KHC regarding their cooperation with the assistance systems, in order to know, for example, how they could use them, how they could communicate. Similarly, assistance systems had a KHC by the way of a simple model of air traffic controllers' tasks, and in particular one assistance system was able to give an estimation of the workload of the radar controller (who manages conflicts inside a sector) (M.-P. Pacaux-Lemoine & Debernard, 2002). Nevertheless, even if reliability is high, other characteristics may put trust into question (Lyons & Guznov, 2018). That is the reason why we are analyzing agents' interaction in more depth through the definition of KHC.

With *the internal part of KHC,* agents try to build up shared mental models (Rouse, Cannon-Bowers, & Salas, 1992) or compatible mental models (M P Pacaux-Lemoine & Loiselet, 2002; Flemisch, Kelsch, Löper, Schieben, & Schindler, 2008). In order to build up such a Common Frame of Reference (COFOR) (Jean Michel Hoc, 2001), cooperative agents need to observe and to communicate, so that agents will build up a

model of each other in parallel. For example, a human agent needs to understand the automation reasoning processes and activities in order to be able to control the overall system (D. D. Woods et al., 2004). With a model of the others, agents are more confident and trust each other (J. Lee & Moray, 1992). Lee and See's definition of trust is one of the most widely cited definitions: "the attitude that an agent will help achieve an individual's goals in a situation characterized by uncertainty and vulnerability" (J. D. Lee & See, 2004). An agent may trust the abilities of others, but also the quality of their interaction (Rajaonah, Tricot, Anceaux, & Millot, 2008). Some connections exist between relative trust, self-confidence and confidence in the other (Van Dongen & Van Maanen, 2013). Having a model of others enables the estimation of their intentions, especially if they are accountable (Mary L Cummings, 2003).

Regarding technical agents, Balfe et al. identified several characteristics that can contribute to trust (Balfe, Sharples, & Wilson, 2015). The automation must be reliable, competent, visible, observable, understandable, directable, robust, and accountable; it must provide proactive control and prevent skill degradation. These characteristics are at the same time relevant for KH and for KHC, and must be part of the model that a human may have of a technical agent, and that is what I proposed alongside Makoto Itoh in a Japanese project on car driving (Makoto Itoh & Pacaux-Lemoine, 2018; Muslim, Itoh, & Pacaux-Lemoine, 2017)(cf. Projects on car driving §7.2.1). Indeed, with models, other agents' behaviors are more predictable and interaction can be more constructive. However, too much trust may lead to unacceptable effects, such as "overtrust" and "overreliance" when an agent overestimates other agents' abilities (Toshiyuki Inagaki & Itoh, 2010, 2013), "complacency" when an agent underestimates process state evolution (Billings, 1996), and "neglect" effects when there is not enough mutual control between agents (Goodrich et al., 2001). Such extreme effects may lead to a total dependency of one agent regarding the high implication of others, and lead to the risk for the agent to lose the feeling of being in control of the situation (Biester & Bosch, 2005). Nevertheless, involvement of agent is linked to the willingness to cooperate (Rajaonah et al., 2008)(Nevo, Benbasat, & Wand, 2012), but also to the responsibility that can be considered such as a motivational factor (Van Dongen & Van Maanen, 2013). That is the affective part of the cooperation (Skjerve & Skraaning, 2004). In the air traffic control study, participants trusted the assistance systems because they learned their KH and KHC which were clear, easily usable and responding to some of their needs, especially regarding the organization of their functions, however responsibility was still an outstanding issue (Frank Flemisch et al., 2012).

One way to build up such a model of others is to communicate with each other or at least to observe the other. The *external part of KHC* has to support communications or observations. Three main ways allow reaching these goals: — agents carry out direct observations of others (movements, mimics, emotions…), — agents have verbal exchanges or they communicate through mediation tools, — agents analyze the activity of others through their effect of the others' actions on the process.

More and more diagnosis systems to analyze human agent's behavior and state do exist, like (motion capture, analysis of physiological data such as heart rate, electro dermal activity, and eye tracking…). With these types of systems, technical agents receive some information to build up and update their human model. When two humans cooperate, they usually analyze the behavior of the other human's state according to voice intonation and mimics in order to identify the current state. Several examples were found in the project with Dassault aviation and DGA, where we analyzed cooperation in a two-seated fighter aircraft, between a pilot and a

weapon system officer (M P Pacaux-Lemoine & Loiselet, 2002)(cf. Project about fighter aircraft crew §7.3). It was especially useful for the weapon system officer to know when he was allowed to interrupt the pilot's individual activity in order to give him a cooperative activity to take part in. When possible, they could communicate and so make explicit the supposed activity or state of the other that was otherwise only based on visual or audio perceptions. In this case, agents needed to have a common code of communication in order to be able to receive and to understand information from others and to transmit comprehensible information to others. With a model of others, agents can adapt information they want to transmit to the potential receiver. With mediated communication, visual, audio, tactical or haptic aids transmit information. Such aids could be useful for agents to share their understanding of the situation and to negotiate decision making if necessary, mainly when cooperation is asynchronous. This kind of cooperation tool, we called *Common Work Space* (M.-P. Pacaux-Lemoine & Debernard, 2002), is detailed in the next section.

3.2.3 The Common Work Space

Several authors in various work domains have already put forwards the notion of work space. In the Air Traffic Control domain, Bentley *et al.* proposed a shared work space which provides an adapted presentation of the air traffic to different users, on different machines, to make the use of shared entities easier (Bentley, Rodden, Sawyer, & Sommerville, 1992). In their work, the shared work space is limited to the external environment and to the representation of the process. Other authors enrich the work space by several elements related to the activity of each agent, and not by raw information but also elaborated ones. Decortis and Pavard define the shared cognitive environment as a set of facts and hypothesis which are a subset of the cognitive universe of each agent (Decortis & Pavard, 1994). In the specific field of Knowledge Based Systems, Brézillon and Pomerol pointed out the necessity for human and assistance system to share a contextual knowledge (Brézillon & Pomerol, 1999). For these authors, it is necessary to share the cognitive representations in order to agree the contextual knowledge of problem solving, to enable the following of each other's reasoning, the exchange of explanation and to control the interaction. Moreover, Royer specifies that a system is all the more cooperative since the cooperation implies more levels, such as perception, analysis, decision and action (Royer, 1994). Indeed, Karsenty underlines the relevance of a shared problem representation to support the process of explanation during which co-workers articulate their individual problem representations and thus, build a richer shared problem representation, rend a deeper analysis of the decision space, and thus reach a better decision (Karsenty, 2000). In the same year, Sonnenwald and Pierce dealt with "Interwoven Situational Awareness", which is "the continuous extraction of environmental information, integration of this information with previous knowledge to form a coherent mental picture in directing further perception and anticipating future events" (Sonnenwald & Pierce, 2000). They propose an interwoven situational awareness that includes the individual, intra group and inter group situational awareness for the Control and Command team members. Indeed, team members need to collect, synthesize and disseminate information to create an understanding of the current battlefield situation and to anticipate future battlefield events. The situational awareness is based on information about the dynamic work goal and situation (the environmental information: mission, enemy, terrain/weather, troops and time available), the work process (tasks, formal and informal task procedures) and specialized field knowledge (information about battle tactics, decision analysis algorithms or methods, biological chemicals, enemy profiles/characteristics, telecommunications networks, civilian government…). Jones and Jasek integrate the same idea into the building of an Intelligent Support for Activity Management

(ISAM) which allows the sharing of goals, contextual information and allocation of functions between the agents (P. Jones & Jasek, 1997). Gutwin and Greenberg highlight the importance for integrating the activity of the other agents and deal with a work space awareness which is "the up-to-the-moment understanding of another person's interaction with the shared workspace" (Gutwin & Greenberg, 1999). The shared work space allows agents to know who is working, what they are doing, where they are working, when various events happen and how those events occur. The environment provides such knowledge that enables actions to be performed or potential actions to be explored.

Cooperative agents develop and maintain a Common Frame Of Reference (COFOR), which is the common part of their respective current representation of the situation. Common Work Space (CWS) is the external support of the COFOR (M P Pacaux-Lemoine & Loiselet, 2002)(cf. Fig. 21). CWS is the external support of a combination of the representation of process states and agents' "mental states", called internal current representation on the figure. CWS is a tool for shared or mutual cognitive environment (Rognin, Salembier, & Zouinar, 2000; Sperber & Wilson, 1987). Sperber and Wilson assert that "A mutual cognitive environment gives each of those who share it evidence of the other's beliefs, including, to some extent, beliefs about the other's beliefs, provided they also have evidence of where the other's attention has been and is going".

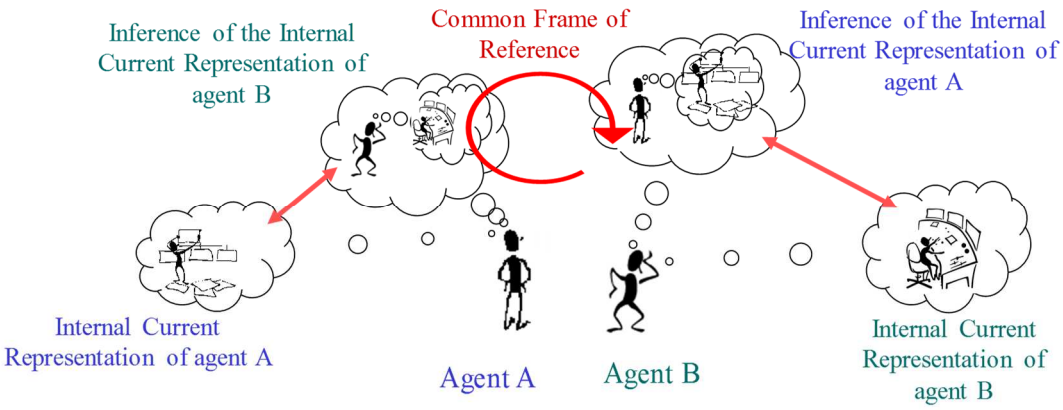

Fig. 21 Updating the Common Frame of Reference, adapted from (M P Pacaux-Lemoine & Loiselet, 2002)

Fig. 22 demonstrates a schema detailing the interest of CWS during cooperative activities. A representation of process or situation states provide input to agent 1 and agent 2 by direct observation or through interfaces by gathering information from process. These interfaces also allow the agent to act on the process (bidirectional arrows between Ag_i internal KH and Ag_i's interfaces). Therefore, each agent develops and maintains one-agent situation awareness regarding the process state (SA) (unidirectional dotted arrows between Ag_i SA and Ag_i's interfaces), but also team situation awareness (team-SA) (Patrick Millot & Pacaux-Lemoine, 2013). CWS can in fact also support cooperative activities. By means of CWS, agents can provide information concerning they own current and future individual activity, but also diagnosis, advices or orders concerning cooperative activity. Supporting such cooperative activities can help humans not to be detracted from their own task (Baker & Yanco, 2004b). Team-SA and COFOR are built in parallel. They result from interference management, *i.e.* differences which might appear between one-agent situation awareness and the inference of the other-agent situation awareness (red zone between Ag_1 SA and inference of Ag_2 SA). In the

project about fighter aircraft crew and cooperative activity, pilot and weapon systems officers may have a different situation awareness because they have different activities and KH, which lead both to focus their attention on different aspects of the situation (cf. §7.3). Nevertheless, when they have to cooperate on a common task, *e.g.* pilot controls aircraft trajectory and weapon systems officer illuminates a target, they have to adjust their SA in order to reach a common frame of reference.

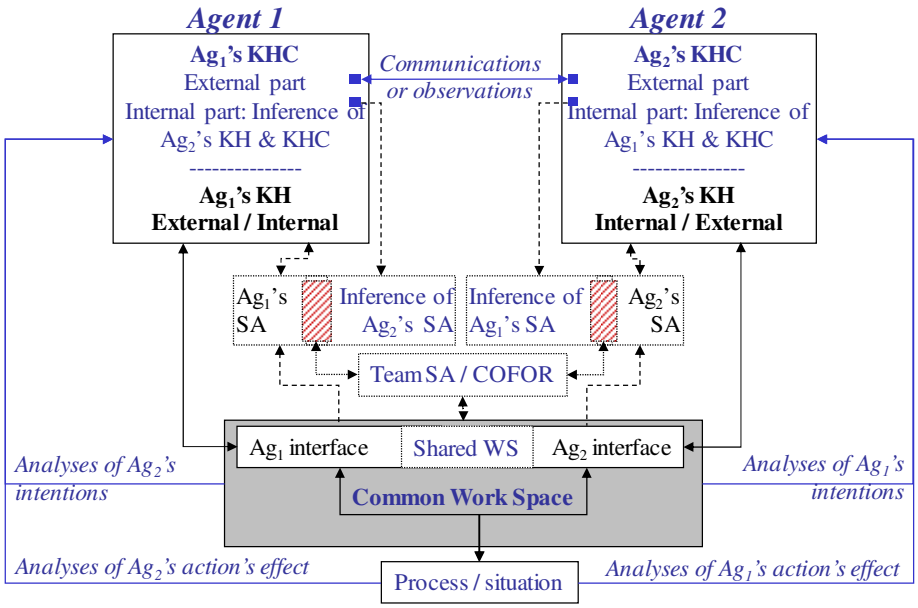

Fig. 22 Cooperative activities through agents Know-How (Ag_i KH), agents Know-How-To-Cooperate (Ag_i KHC), agents Situation Awareness (Ag_i SA), Common Frame of Reference (COFOR), team Situation Awareness (Team SA) and Common Work Space

The use of the other's model, so part of the KHC, makes the management of interferences easier. Fig. 22 highlights three ways for an agent to get information about the other and to build such a model. The first one is direct through *communications and observations*. However, this method is time consuming and may disturb the other. The second method is less direct and involves *analyzing Ag_1's actions effects* through the process evolution. This method involve too many inferences. The last method is the use of the CWS on which each agent activity is more obvious as well as *other agent's intentions*. Bratman (1992) in (Shu & Furuta, 2005) underlined the benefit to have such information and made the hypothesis that agents attempt to be responsive to both the intention and action of others, and know that others are attempting to be similarly responsive. He called this behavior "mutual responsiveness".

This section presented the way agents may build and enrich individual and team situation awareness, especially with the use of the CWS. Sasangohar *et al.* also emphasize benefits to have and maintain SA, especially when events interrupt tasks in progress. They proposed a decision aid similar to a CWS and they demonstrate this assistance that highlights the main points of the situation, and they plot out the evolution of the SA from a chronological account of events (Sasangohar, Scott, & Cummings, 2014). The next section gathers the notions presented in the previous parts, "Know-How", "Know-How-to-Cooperate" and "Common Work Space", and combines them in order to propose a generic model of cooperative agents' interaction, model more suitable for an engineering approach and for automation designers.

3.2.4 Towards a generic model of cooperative agents' interaction

Literature on human-machine systems, human decisional processing, human-machine organizations, situation awareness leads us to design tools, KH, KHC and CWS, that we are now able to adjust together as a mechanism that we wish to design and control. This mechanism is an aid for the designer to identify all the necessary functions an assistance system must have, but also that a human may have, training to build models, and how to support interaction between human and assistance system. Moreover, designers can implement this mechanism to have dynamic control over human-machine organization according to function allocation, rules and other types of key elements we will present in the following sections.

Paragraphs 3.2.1 and 3.2.2 gave a detailed presentation of agents' KH and KHC, but as we would like to provide methods to the designer and to be able to implement these entities, we need to bring together the main objectives of the cooperation and propose a few functions as a synthesis of these objectives. From a designer's point of view, KH and KHC can consist of two parallel functions (or task in object-oriented and multi-tasking programming), and each one integrates four sub-functions.

The functions proposed by Parasuraman *et al.* to specify levels of automation (presented in §2.2.4) define the four sub-functions of the KH. Agent may gather information about the process, analyze gathered information to diagnose/forecast process state, find solutions and select one to make a decision, and implement the decision by sending a command to the process. As explained in §2.1.1 and shown in Fig. 4 (Rasmussen model), shortcuts may prevent the agent from completing the four sub-functions if the agent is skilled with the process or an expert (cf. Fig. 5).

To define the sub-functions of the KHC, we must put together the goals of cooperation given in the definition of cooperation proposed by Hoc (presented in §3.1), and the goal of being aware of others (team situation awareness concept, cf. §2.3.1), and finally, the goal to decide task allocation (concepts about human-machine system organization and authority management, cf. §2.2). Therefore, a cooperative agent has to:

- gather information about teammate agent, in order to have a representation of the current KH and KHC of the other agent (or their usual KH and KHC when models exits),
- detect potential interference between their understanding of the situation (the result stemming from their KH function),
- manage interferences by negotiation, accepting the solution of the other, or imposition of solution to the other,
- decide who manages decisions and actions by task allocation.

Fig. 23 shows a representation of KH and KHC functions in a human-machine system with the automation domain point of view. This model highlights several possible interactions between human and automation (Marie-Pierre Pacaux-Lemoine & Itoh, 2015). KH functions of agents interact by the means of the Common Work Space represented by the blue rectangle with four scales between human and automation parts (scales are based on Parasuraman et al. and Flemisch et al. representations, cf. Fig. 14 and Fig. 15). KHC functions of agents use information provided by the Common Work Space in order to build a model of the other agent (rectangles on the left part of the schema) and to evaluate this agent's involvement in the process control. The

results of this evaluation, compared to the own involvement and model of oneself (interference detection and management), have to lead to the adjustment of the position of sliders that describe the functions allocation (scales represented in the Common Work Space). The scales associated to each KH functions have the same objectives as the scale proposed by Flemisch et al. (2003) (cf. §2.2.4).

The method of representation demonstrated by Fig. 23 makes it possible to gather all the types of organization proposed with the structures, forms and modes of cooperation (§2.2).

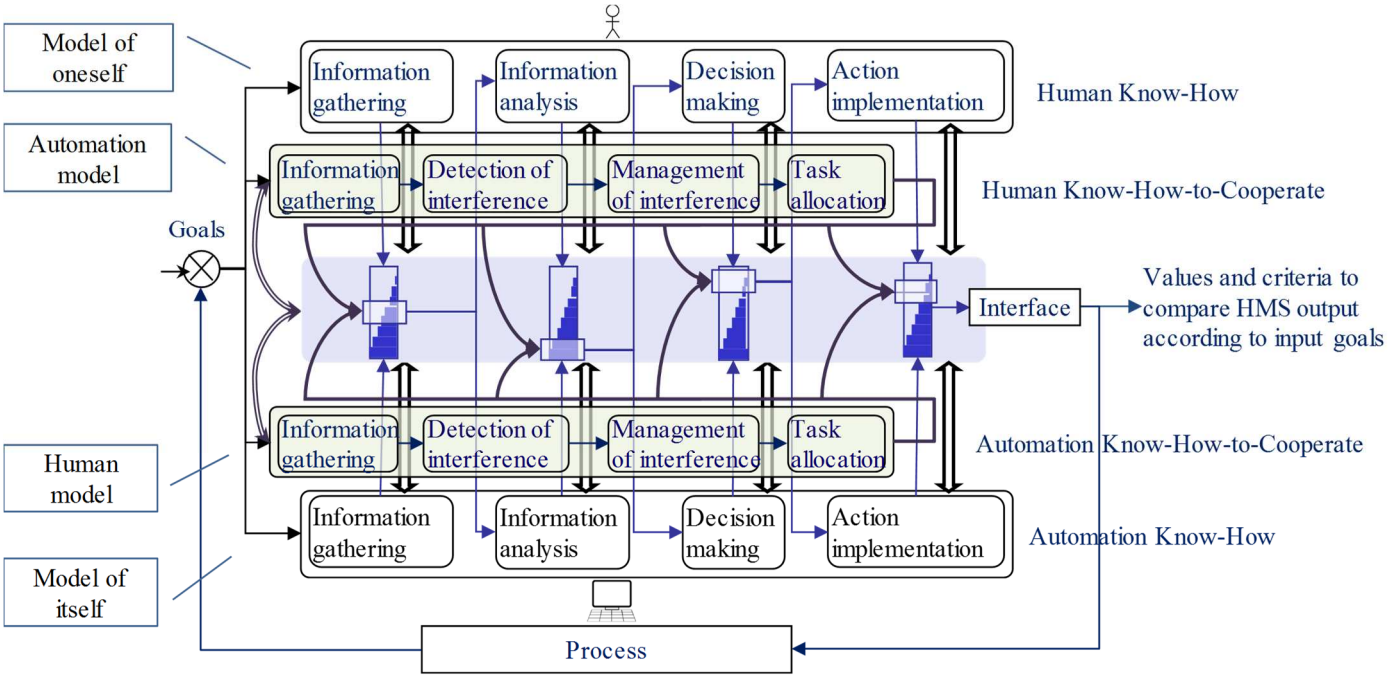

Fig. 23 Model of cooperative agents' interaction, adapted from (Marie-Pierre Pacaux-Lemoine & Itoh, 2015) (Marie Pierre Pacaux-Lemoine & Flemisch, 2018)

The position of the slider on the scale defines the degree or the percentage of sharing between human and automation functions. Either automation or human can manage some functions alone according to their competency and capacity (slider completely on one side), but also according to how they can take into account the activity of the other. Therefore, agents have to identify and implement adequate coordination of the four KH functions. The blue rectangles with scale and thin blue straight arrows between each KH function of Fig. 23 represent such a coordination. It must define the best balance between each agent's involvement, and so find the right place for the slider on the scale for a specific situation. Such a representation may suggest a smooth shifting control authority (Abbink, Mulder, & Boer, 2012). The control of the slider identifies who has the authority. Agents may have the *authority to initiate* and the *authority to terminate* a function (Goodrich et al., 2001). However, this definition focuses on KH functions. Regarding KHC functions, Inagaki defined the *human-initiated automation invocation* and the *system-initiated automation invocation* (T. Inagaki, 2003; Scerbo, 1996). Another way to proceed is to offer the human the possibility of an allocation decision made by the machine, called *autonomy mode suggestion* (Baker & Yanco, 2004b). In the automation invocation strategies, Inagaki proposed initiating cooperation in the case of critical events, the so-called critical-event strategies (T. Inagaki, 2003). Machine prepares an action and waits for human agreement. Information about the human is the basis of the two other strategies proposed by Inagaki. In this case, agents need to have model

of the other agents (rectangles on the left side of Fig. 23). Agents provide information about themselves in order to permit others to update their KHC. The *measurement-based driven strategy* deals with gathering current information about human agent state (workload, attention…) and *model-based driven strategy*, deals with the use of models to predict the performance of human agents (intents, instantaneous capabilities, resources).

This model was proposed, and was very useful, during the project with Thalès and DGA (French Defense) about Human-Robot Cooperation (cf. §7.4.2). We studied the cooperation between a remote human operator who had to do reconnaissance in a risky environment and a robot that was able to control its trajectory during specific kinds of situation. We identified the KH and KHC functions that both human and robot needed to reach efficient cooperation, but also cooperation that is well accepted by the human who was the DGA teleoperators (cf. Table 7 in §7.4.2). Another example of these functions is provided in the chapter about the design method in the case of cooperation study between car driver and driving assistance system (cf. §Fig. 33).

According to the type of situation, events and the state of agents, human and machine have, most of the time, different KH and KHC. Differences can be ranked, which is what we did with the definition of Levels of Cooperation (LoC). LoC use a simple ranking of KH and KHC in order to provide a method to identify possible types of cooperation (Marie-Pierre Pacaux-Lemoine & Vanderhaegen, 2013b). We imagine that an agent builds up a model of the other agent, *i.e.* their KH and KHC, in terms of Benefit, Cost and Deficit.

The so-called BCD (Benefit/Cost/Deficit) model was initially developed to assess the consequences of human errors on several criteria related to technical or human performance or state (Frédéric Vanderhaegen, 2004). These consequences can be positive or negative. Regarding a reference situation, benefits, costs and possible deficits can assess a given human behavior:

- The benefits due to the success of the control of a given situation.
- The acceptable costs due to the cognitive or physical effort to control a given situation in order to make it successful.
- The unacceptable possible deficit related to the potential occurrence of a hazardous or unprofitable situation, in case of unsuccessful control of a given situation.

As agents compare their own KH and KHC to those of the other, similarities and differences between such abilities emerge. We use the word similarity, instead of equality, because KH or KHC can never be exactly equal, except between two identical machines. KH and KHC define two dimensions that describe Levels of Cooperation, $LoC_{x.y}$. The Table 4 presents the possible LoC according to KH. Cooperation can start if both agents have at least one KH. At $LoC_{1.y}$ one agent has a KHI (internal KH) and the other a KHE (external KH). The first agent analyzes situation and makes decision, and the other gathers information (input) and implements decision (output). A typical example is the remote control of robots. At $LoC_{2.y}$ each agent has a KHI and a KHE, but they are different. Therefore, for the two first levels agents are complementary. At $LoC_{1.y}$ complementarity stands for knowledge and at $LoC_{2.y}$ complementarity stands for process sharing. Both levels can refer respectively to the integrative form and augmentative form of cooperation proposed by Schmidt and presented in §2.2.3. At $LoC_{3.y}$ agents' KH are similar. At this level, agents can debate the results of their

activities. This level can be compared to the debative form of cooperation proposed by Schmidt. The last level, $LoC_{4.y}$, represents a combination of levels 1 to 3.

Table 4 Levels of Cooperation according to KH

LoC/KH	KH_{Ag1} and KH_{Ag2}
0	$KH_{Ag1} = \{\emptyset\}$ or $KH_{Ag2} = \{\emptyset\}$
1	$KHI_{Ag1} = KHE_{Ag2} = \{\emptyset\}$ and $KHE_{Ag1} \neq \{\emptyset\}$ and $KHI_{Ag2} \neq \{\emptyset\}$ and $KH_{Ag1} \cap KH_{Ag2} = \{\emptyset\}$
2	$KH_{Ag1} \neq \{\emptyset\}$ and $KH_{Ag2} \neq \{\emptyset\}$ and $KH_{Ag1} \cap KH_{Ag2} = \{\emptyset\}$
3	$KH_{Ag1} \neq \{\emptyset\}$ and $KH_{Ag2} \neq \{\emptyset\}$ And $KH_{Ag1} \cap KH_{Ag2} = KH_{Ag1} = KH_{Ag2}$
4	$KH_{Ag1} \cap KH_{Ag2} \neq KH_{Ag1} \neq KH_{Ag2} \neq \{\emptyset\}$

The Table 5 presents LoC regarding KHC. Cooperation can start at the $LoC_{x.1}$ when both agents can communicate but are not able to build up a model of the other. It is usually the case when a human uses a system only occasionally. They can exchange information about the results of their respective KH. At $LoC_{x.2}$ only one agent can build up a model of the other. At $LoC_{x.3}$ both agents can build up a model of the other.

Table 5 Levels of Cooperation according to KHC

LoC/KHC	KHC_{Ag1} and KHC_{Ag2}
0	$KHC_{Ag1} = \{\emptyset\}$ and $KHC_{Ag2} = \{\emptyset\}$
1	$KHCE_{Ag1} = KHCE_{Ag2} \neq \{\emptyset\}$ and $KHCI_{Ag1} = KHCI_{Ag2} = \{\emptyset\}$ and $KHC_{Ag1} \cap KHC_{Ag2} = KHCE_{Agi}$
2	$KHCE_{Ag1} = KHCE_{Ag2} \neq \{\emptyset\}$ and $KHCI_{Ag1} = \{\emptyset\}$ and $KHCI_{Ag2} \neq \{\emptyset\}$ and $KHC_{Ag1} \cap KHC_{Ag2} = KHCE_{Agi}$
3	$KHCE_{Ag1} = KHCE_{Ag2} \neq \{\emptyset\}$ and $KHCI_{Ag1} = KHCI_{Ag2} \neq \{\emptyset\}$ and $KHC_{Ag1} \cap KHC_{Ag2} = KHC_{Ag1} = KHC_{Ag2}$

The objective is now to combine levels of each KH and KHC to offer different types of cooperation, so lack of KH can be compensated by better KHC, and vice versa. Table 6 presents such a combination. For example, at $LoC_{1.1}$, agents' individual activities are complementary but dependent, and agents can communicate. Therefore, they can provide or ask each other the results of their respective activities. At $LoC_{1.2}$, there is no change about their KH, they can communicate, but moreover one agent can build up a model of the other. This agent can infer the result that the other would provide. At $LoC_{1.2}$ both agents can make inferences regarding the activity of the other. The cost of $LoC_{1.y}$ is that one agent cannot assess the KH of the other because they do not have the same KH. However, if they have a $LoC_{1.3}$ the benefit is that they have a good model of each other regarding results that they can reach together. In fact, there is a kind of compensation between cost and benefit of each dimension.

Table 6 Matrix of possible levels of Cooperation

LoC/KH \ LoC/KHC	1	2	3
1	$LoC_{1.1}$	$LoC_{1.2}$	$LoC_{1.3}$
2	$LoC_{2.1}$	$LoC_{2.2}$	$LoC_{2.3}$
3	$LoC_{3.1}$	$LoC_{3.2}$	$LoC_{3.3}$
4	$LoC_{4.1}$	$LoC_{4.2}$	$LoC_{4.3}$

Table 6 is a grid to study possible organizations between human and machine. If that is during the design of a new human-machine system with a selected LoC, designers can identify the best KH and KHC for human and for machine. They also identify criteria (defined by BCD (Marie-Pierre Pacaux-Lemoine & Vanderhaegen, 2013a)) in order to have an efficient human-machine system. Moreover, the grid can also assess LoC during human-machine system activity, when KH and/or KHC of agent or environment change.

This approach has been used to identify criteria that could be implemented to decide task allocation between driver and driving assistance systems in case of risky and pre-crash situations (M. Itoh, Pacaux-Lemoine, Robache, & Morvan, 2013; M.-P. Pacaux-Lemoine, Itoh, Morvan, & Vanderhaegen, 2012).

The next section tackles such a dynamic control of task allocation between human and machine by defining the adaptability of levels of automation.

3.3 Adaptability of levels of automation

All the previous sections have asserted the necessity to provide the human-machine system with more flexibility to adapt itself to new events, new environments, changes in the competences and capacities of agents involved in the process control. Adaptability of levels of automation can bring key elements to reach this objective. The previous section dealt with the implementation of a kind of mechanism that may support human-machine system design and dynamic adaptation during its use. This section presents decisional trees able to manage this approach.

Before describing the numerous steps that can lead to adaptability, we would like to present previous studies conducted in the past with the same goal. As written in section §2.2 (page 33), three main performance criteria predefine human-machine system organization: — the reliability resulting after debates, — the adaptability according to competence resulting from adjustment of different *capabilities*, and — the adaptability according to *capacity* resulting from adjustment of workload and energy consumption. Sheridan proposes improving reliability by task sharing or task trading (Thomas B. Sheridan, 1992). With task trading, human agent or artificial agent controls a task (not both), and either of them can transfer the control to the other. With task sharing, human agent and artificial agent can control different aspects of the process in parallel at the same time. Agents can debate the solution because, in this case, they have the same KH.

KH must also be the same when the adaptability is according to capacity. This case appears when the capacity of an agent is not sufficient to perform a task. The relief type of task sharing proposed by Sheridan has such an objective by avoiding human operator overload (Thomas B. Sheridan, 1992). This approach has been used in robotics (Kiener & Stryk, 2010). They distinguish four robot's abilities similar to the ones proposed by Parasuraman, and they define a utility value for each task according to required abilities and cost for completing the task, the preceding and/or the following task and current state of execution (assigned/not assigned or executable/being executed or executed/solved). A robot manages a task if it has the most important utility value for this task. The adaptability is important when the KH of one agent is not sufficient to perform a task. The "extension type of task sharing" proposes such an extension of the capabilities of the human-machine system (Thomas B. Sheridan, 1992).

It is now time to specify the difference between *adaptive* and *adaptable* system. An adaptive system determines and executes the necessary adaptation. For an adaptable system, the human is in charge (Miller & Parasuraman, 2007). Studies usually deal with adaptable systems, even if they attempt to justify, in some specific situations, the interest of providing artificial agent with more authority. Well-known works about adaptability used different notions, such as "sliding autonomy" (Simmons et al., 2007), "adaptive automation" (Cosenzo et al., 2010b; Kaber, Perry, Segall, McClernon, & Prinzel, 2006; D. D. Woods et al., 2004), "adjustable autonomy" (Baker & Yanco, 2004b; Goodrich et al., 2001; Zieba, Polet, & Vanderhaegen, 2011), "situation adaptive autonomy" (T. Inagaki, 2006) or "mixed-autonomy" (Barber, Davis, Nicholson, Finkelstein, & Chen, 2008; Finzi & Orlandini, 2005; Goodrich et al., 2001).

These studies usually tried to respond to a specific objective, in most cases from a specific domain. We would like to propose a generic procedure to examine and implement adaptive and adaptable human-machine system (L. Habib, Pacaux-Lemoine, & Millot, 2017b). This study has been conducted as part of **the PhD of Lydia Habib** (Lydia Habib, 2019). The two next graphs illustrate such a generic procedure based only on the ability for an agent to complete or not (1 or 0) the four functions of the KH and the four functions of the KHC, presented in Fig. 24 and Fig. 25 respectively. It is of course very restrictive to decide if an agent can or cannot complete a function, especially to describe human activity, but it is the first step for applying this method. We will extend the number of possibilities to share functions in order to achieve more adaptability. A fuzzy method, for example, could suit this need. Therefore, using this simple binary approach, three cases are possible, [1 0] only human has the KH or the KHC, [0 1] only machine has the KH or the KHC, and [1 1] both human and machine have the KH and the KHC.

At the first function of the KH, information gathering, the agent who has the KH gets information from the process (cf. Fig. 24). Then if the agent has the ability to cooperate, the agent may interact with the other agent. Cooperation is represented by the blue diamond on both trees (Fig. 24 and Fig. 25). However, the other agent can also trigger the cooperation because, for example, this agent has to make a decision without being able to gather information. The Common Work Space helps manage such cooperation and shares information by providing common language and tools to organize exchanges between agents.

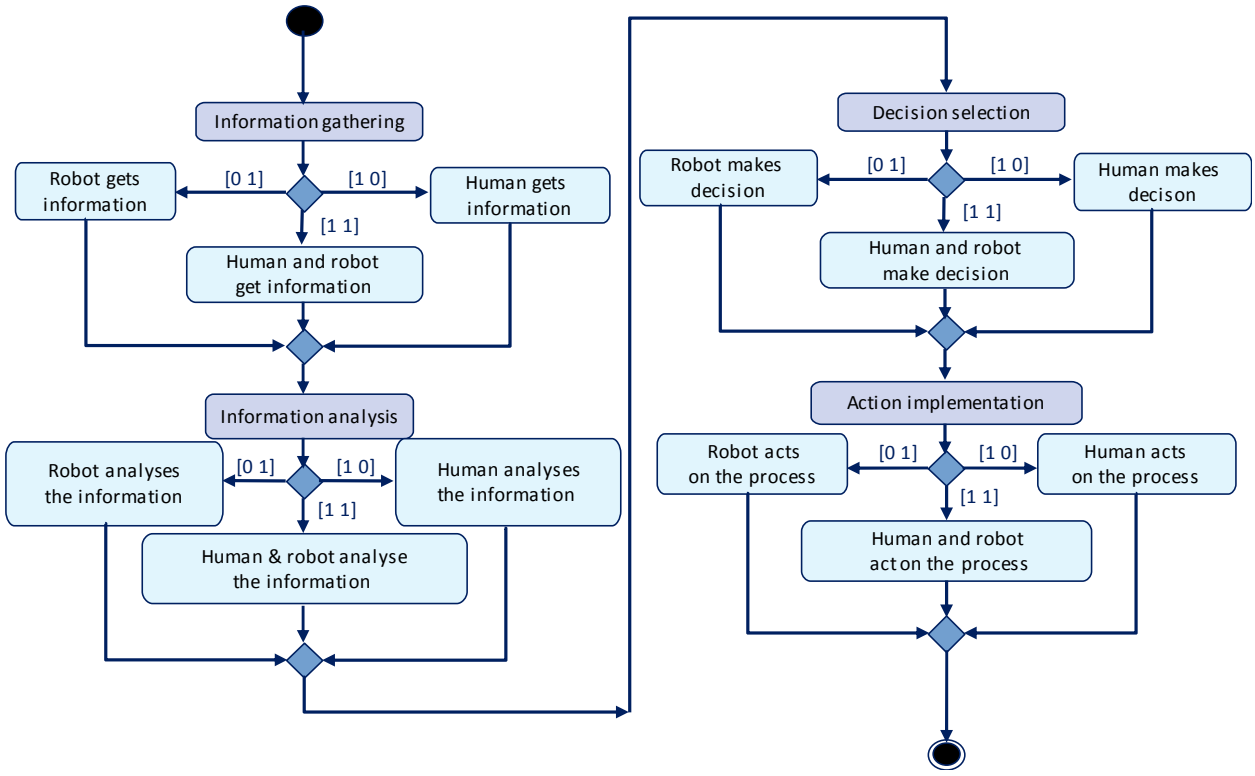

Fig. 24 Human-Machine function allocation regarding KH, adapted from (L. Habib et al., 2017b)

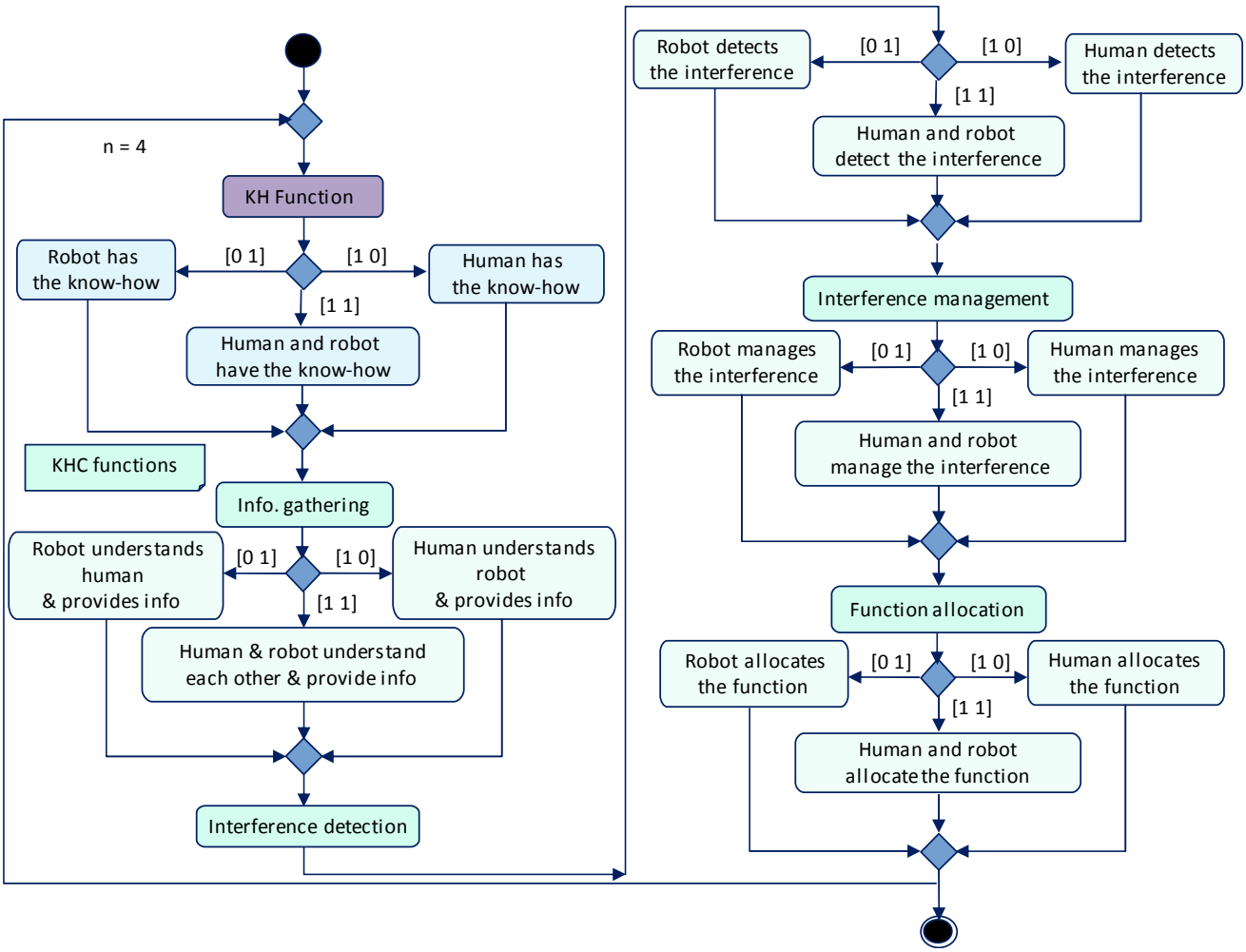

Fig. 25 Human-Machine function allocation regarding KHC, adapted from (L. Habib et al., 2017b)

The agent who initiates cooperation gathers information about the other agent, or can ask for information if the other agent can answer (cf. Fig. 25). The result of this function is the input of the next KHC function, the interference detection. In this function, the agent who has the interference detection ability detects potential interferences between the results of the KH function of each one. The result of this function supplies the interference management function performed by one of the agents or the both. When both agents manage the interferences, they impose, accept or negotiate their result in the next step dealing with the function allocation. This KHC function decides the allocation of the KH function according to the previous result. After this step, the next KH functions follow the same procedure, until the last KH function.

We had the opportunity to work with the University College of London and Tom Carlson, and we aimed to study how Human-Machine Cooperation principles may help design a cooperative Brain-Computer Interface to control robot (cf. §7.4.4; p.153). Using the approach presented below, we extracted four levels of cooperation between a robot and a human who can only use their "thoughts" to send commands.

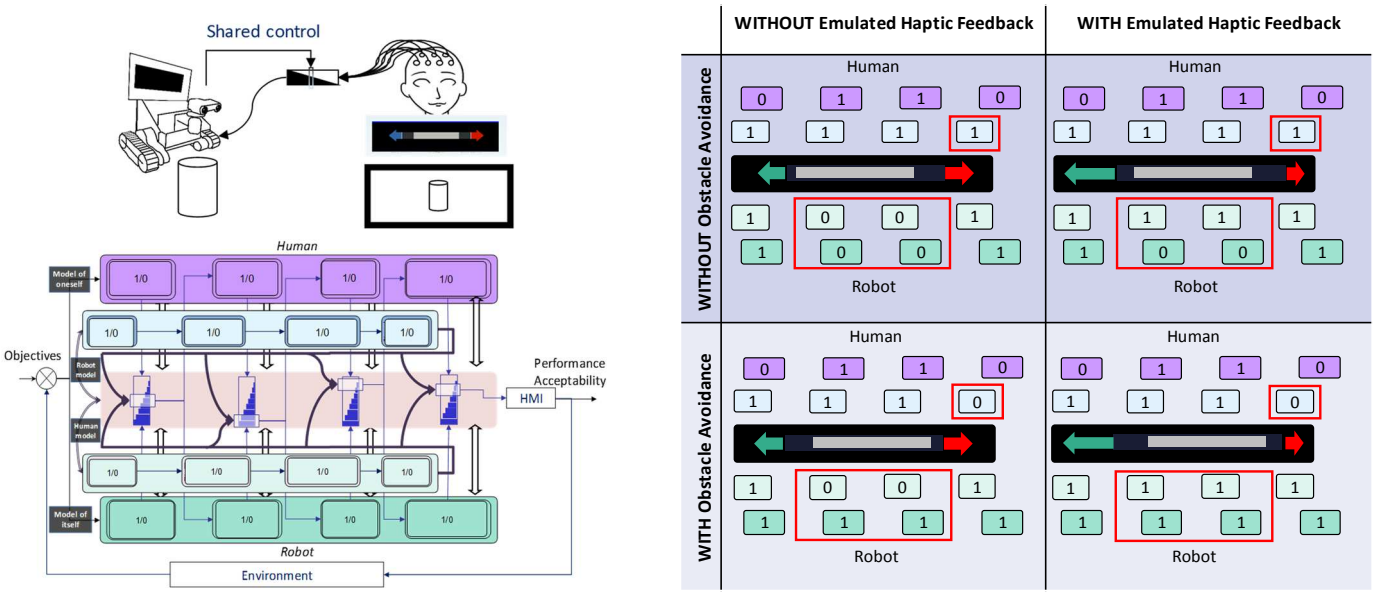

Fig. 26 Emulated-haptic feedback experiments: KH of Human and robot (violet and green rectangles respectively) and their KHC (light blue and green rectangles). If the agent has the ability to perform a sub-function, "1" is written in the rectangle.

In the above explanation, one piece of information or one event triggers the procedure with the sequence of KH and KHC functions. When agents have no expertise or experience to control a process, or to cooperate with the other agent, usually they strictly observe such a procedure. Nevertheless, most of time some shortcuts can accelerate decisions. It is true for the KH, as described in Fig. 5 (p. 31), but it is also true for the KHC. Therefore, we proposed an extension of Rasmussen model in order to identify the experience and the expertise of an agent to cooperate with other agents (L. Habib et al., 2017b). Three types of cooperative behavior respond to this objective. In the *KHC skill-based behavior*, human and machine are accustomed to working together. They have an adequate model of each other and they can anticipate what the intentions and actions of the other could be, cooperation is implicit (no need to ask, to justify, to negotiate), integrative and/or augmentative (no need to debate). In the *KHC rule-based behavior*, human and machine need to have a little bit more information about the other. They have a model of each other but they need information regarding

how the model of each other could be instantiated in a situation they have not yet come across. Cooperation is more explicit and needs some exchanges to debate the best instantiation. In the *KCH knowledge-based*, human and machine have to build or to improve the model they have of each other. Cooperation is again more explicit and needs negotiations to plan task sharing, task trading and criteria for such decisions.

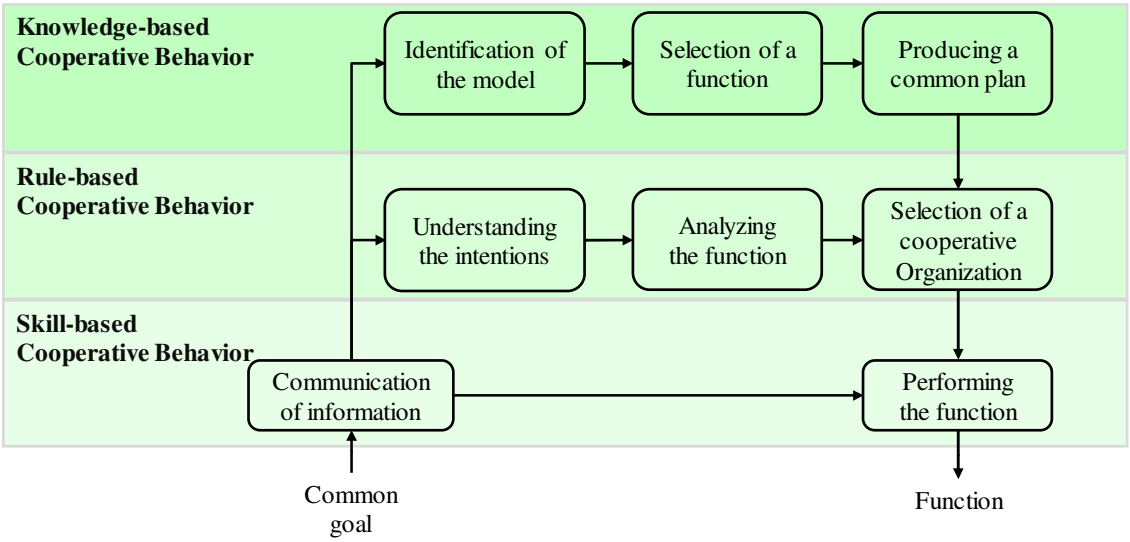

Fig. 27 Extension of Rasmussen model to cooperative behavior (L. Habib et al., 2017b)

Training usually concerns KH functions, *but the training to work with colleagues or with new assistance systems is also a key point of good cooperation as we saw in the projects in Air Traffic Control, with Fighter aircraft crew and with Thalès/DGA staff* (cf. §7.1, §7.3 and §7.4.2). Indeed, as we saw in these applications, humans usually work with same teammates. They know each other very well because they spend time together, they solve problems together, and they know strengths, weaknesses, habits, and many other things about the others. They demonstrate skill-based cooperative behavior in most of the task. When several cooperative tasks are skill-based, the cooperative agents may manage additional complex and difficult cooperative tasks without affecting their performance. Team training issues have not been studied enough. Salas et al. made some proposals about what, when and how to train (Salas et al., 1995), and we will discuss this aspect in the next chapter about methodology.

All presentations and explanations until now, stemming from the literature and models we proposed, have focused on interaction and cooperation between two agents, except when dealing with the assisted explicit mode of cooperation. Indeed, in this mode, we integrate agents from an upper decisional level. In fact, agents are rarely the only two to control process. They control a part of an overall process in which several other agents are involved with similar or complementary objectives. With the increase of process complexity, but at the same time the increase of machine abilities, the gathering of all human-machine systems extends towards socio-cyber-physical-systems. Therefore, we need to consider most humans and machines involved at different decisional levels of the overall process. We believe that the model of cooperative agent and the model of cooperative agents' interaction may help identify individual and cooperative activities of humans and machines in order to reach cooperative socio-cyber-physical-systems. This is the goal of the next section. It deals with cooperation between several levels of activity, or several levels of abstraction, sometimes defined according to hierarchical levels.

3.4 Multi-level cooperation

Process control and supervision represent different types of activity, from the more reactive and short-term part close to the commands of the process, to the more planned and long-term part close to the planning level. In the case of automation and especially in the case of the human-machine system, three levels are mainly used (M.-P. Lemoine et al., 1996; Michon, 1985). The planning level, also called the strategic level, has the goal of defining the plan of the activity. The tactical level's goal is to apply the plan by triggering the defined tasks or to update the plan according to new events, changes in the resources or new objectives. The operational level has the objective of controlling the process. One or several agents may manage each level, and an agent may take part of one or several levels. Therefore, it appears important to define such a cooperation that we called multi-level cooperation (M.-P. Lemoine et al., 1996). Indeed, cooperation between levels concerns interactions about KH or KHC of human or machine. Objectives, decisions and orders, managed by the KH of agents, evolve from higher decisional levels (planning or tactical) to lower levels close to command/control of process. In reverse, events and information update stem from lower levels and are sent to upper levels. Regarding the KHC of agents, one main difference between levels is the time the human or the machine can allocate to cooperative task. At the operational level, time pressure to perform individual task is sometimes too high to allow spending time to cooperate. At the operational level, agents usually cooperate for action implementation with traded or shared control. At this level, cooperation is generally prepared because there is no time to debate the best solution. In that case, the human or the machine has the authority to decide action according to the complexity or the emergency of the situation (Marie Pierre Pacaux-Lemoine, 2014). We had paid particular attention to the shared control concept, and we decided to extend the model of cooperation used for two agents to other agents involved in other levels (Marie-Pierre Pacaux-Lemoine & Itoh, 2015). Therefore, cooperation between levels can have several forms, and the CWS used in each level can take into account the CWS of other levels (cf. Fig. 28).

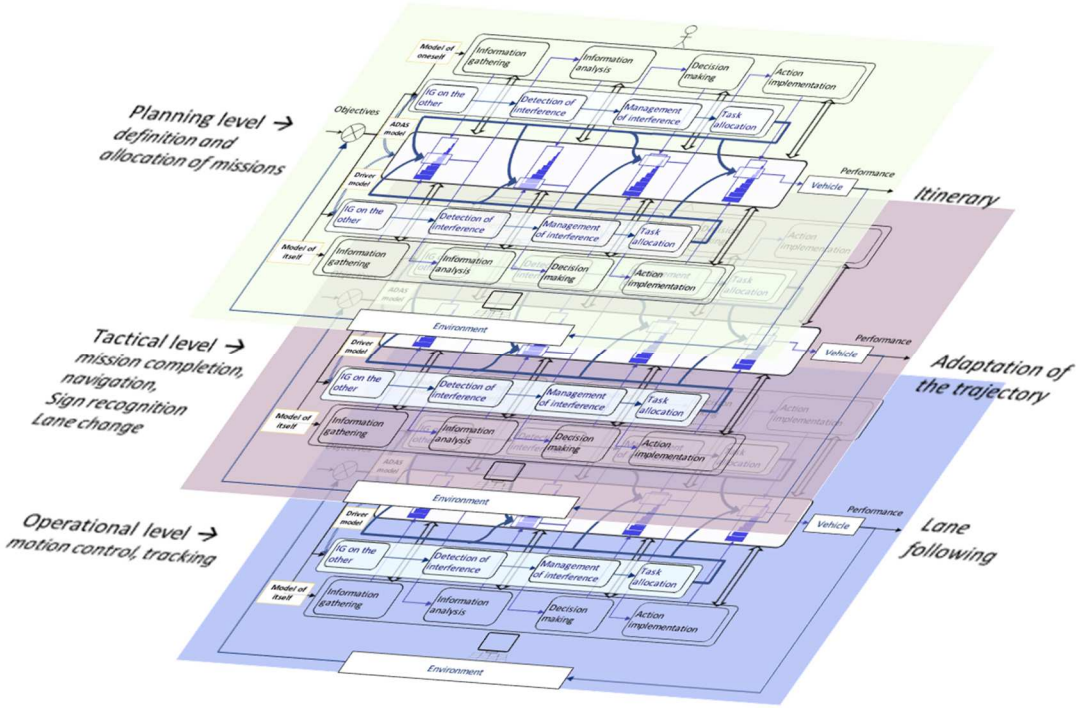

Fig. 28 Multi-level cooperation, adapted from (Marie-Pierre Pacaux-Lemoine & Itoh, 2015)

A useful project to exemplify multi-level cooperation with several humans and technical agents is the project conducted in crisis management (cf. §7.4.3, p.150). The study of firefighters' activity and crisis unit management highlighted three main levels of activity (cf. Fig. 29). The crisis unit of a firefighter department or the crisis unit of a city (with a sub-prefect as decision-maker) is at the strategic level and decides missions and allocates resources. The command post vehicle with several officers, usually close to the hostile environment, is at the tactical level. They received commands from the strategical level and they provide contextual and adapted information to the operational level where several other firefighters are involved. Each level is supported by technical agents, *i.e.* decision support systems at all the levels according to the needs (raw to precise information, time span...), and robots at the operation level. Therefore, cooperation is supported at each level, not only by its own CWS, but also between levels with an adaptation of CWS, like a kind of zoom in to focus on the operational level or zoom out for a broader view at the strategic level.

Fig. 29 Multi-level cooperation in crisis management

Several authors have already studied cooperative activities implemented at each level and the model of cooperation we propose may implement these multi-level cooperative activities.

Cooperation at strategic level concerns "cooperation in plan" (Loiselet & Hoc, 2001), "Plan based direction" (D. D. Woods et al., 2004), "planning control" (Simmons et al., 2007), "mission management control loop" (M L Cummings & Mitchell, 2007). Cooperative activities may concern the planning of individual tasks as well as the planning of cooperative tasks such like meeting points. In the "planning-based interaction of the mixed-initiative approach" proposed by Finzi and Orlandini, cooperative activities are planned in order to limit interaction between levels (Finzi & Orlandini, 2005).

Cooperation at tactical level concerns the cooperation that consists in updating and executing the plan. In the "cooperation-based interaction of the mixed-initiative approach" proposed by Finzi and Orlandini, humans can add new tasks to the plan and the machine validates. Goodrich et al. proposed a similar approach. It concerned the mode of autonomy with "goal-biased autonomy", for which the geographic zone and a goal are defined by human (Goodrich et al., 2001). In the "Direction through commanders' intent", proposed by Woods et al., the cooperative objective is to adapt a plan for disruptions and opportunities (D. D. Woods et al., 2004). "Executive control" (Simmons et al., 2007), "navigation control loop" (M L Cummings & Mitchell, 2007) also refer to tactical level. Allen and Ferguson propose an "automated plan reasoning system" to support collaborative planning in the case of evacuation-planning domain (Allen & Ferguson, 2002). They address tactical levels with three possible problem-solving operations: suggesting a new goal, extending an existing solution and modifying a parameter of a solution.

Cooperation at operational level concerns "cooperation in action" (Loiselet & Hoc, 2001). At this level, agents are mainly reactive and they have no time to negotiate, but they must adjust their respective actions. In the "operator-based interaction of the mixed-initiative approach" proposed by Finzi and Orlandini, humans have to trigger interaction frequently (Finzi & Orlandini, 2005). A similar approach, proposed by Goodrich *et al.* with "the intelligent teleoperation" (safe mode, shared control/allocation of control), promotes continuing interaction between human and machine (Goodrich et al., 2001). Another way to control operational level tasks is to use constraints. With "Constraint based direction" proposed by Woods et al. (D. D. Woods et al., 2004), or waypoints and heuristics proposed by Goodrich et al., attractive or repulsive potential fields and constraints are used to control individual tasks by an indirect cooperation. Therefore, this level relates more behavioral control (Simmons et al., 2007) and motion control loop (M L Cummings & Mitchell, 2007).

These studies highlight several possibilities of cooperation at each level but there is little information dealing with what is cooperation between these levels. In other words, we could write how a human-in-the-loop can cooperate with a human-on-the-loop (Schirner, Erdogmus, Chowdhury, & Padir, 2013), but what about cooperation between agents-in-the-loop and agents-on-the-loop? Tactical and strategic levels implement more and more assistance systems, but problems start to appear, like the loss of flexibility at operational level when the assistance system at tactical level imposes rigid organization. Examples of this problem already come from different domains like in the railway industry (Balfe et al., 2015), and problems of interaction between levels are also already underlined by the military domain in which implementation of new technology is rapid but risky. The UK Ministry of Defense Crown published a report about human-machine teaming that warns about such risks. They wrote, "The interdependencies between technologies, tactics and strategy are likely to be complex. Our understanding must be improved through research, experimentation and training" (UK Ministry of Defence Crown, 2018). That was the objective when we studied links between levels gathering the concepts of shared control, shared and cooperative guidance and control, and human-machine cooperation (F. Flemisch, Abbink, Itoh, Pacaux-Lemoine, & Weßel, 2016) (cf. Fig. 30).

Shared control seems to focus on the common task or function on operational level, while cooperation includes a way of taking increasingly into account the other agent and the other levels. In line with the above, as well as knowing what the other is doing, cooperation creates the possibility of having a model of the partner in order to know how they can cooperate. A cooperative agent (that has KHC) can gather information about the other, analyze this information in order to make a decision about their cooperation. Such activity can go directly back again to the operational level. Nevertheless, tactical and strategic levels should prepare such cooperative activity that may even be prepared and maintained with communication that is not concerned about operational, tactical or strategic levels at all. An additional level should supervise and manage cooperative activity. We called this the cooperational level and it is transversal to the three other cooperation levels.

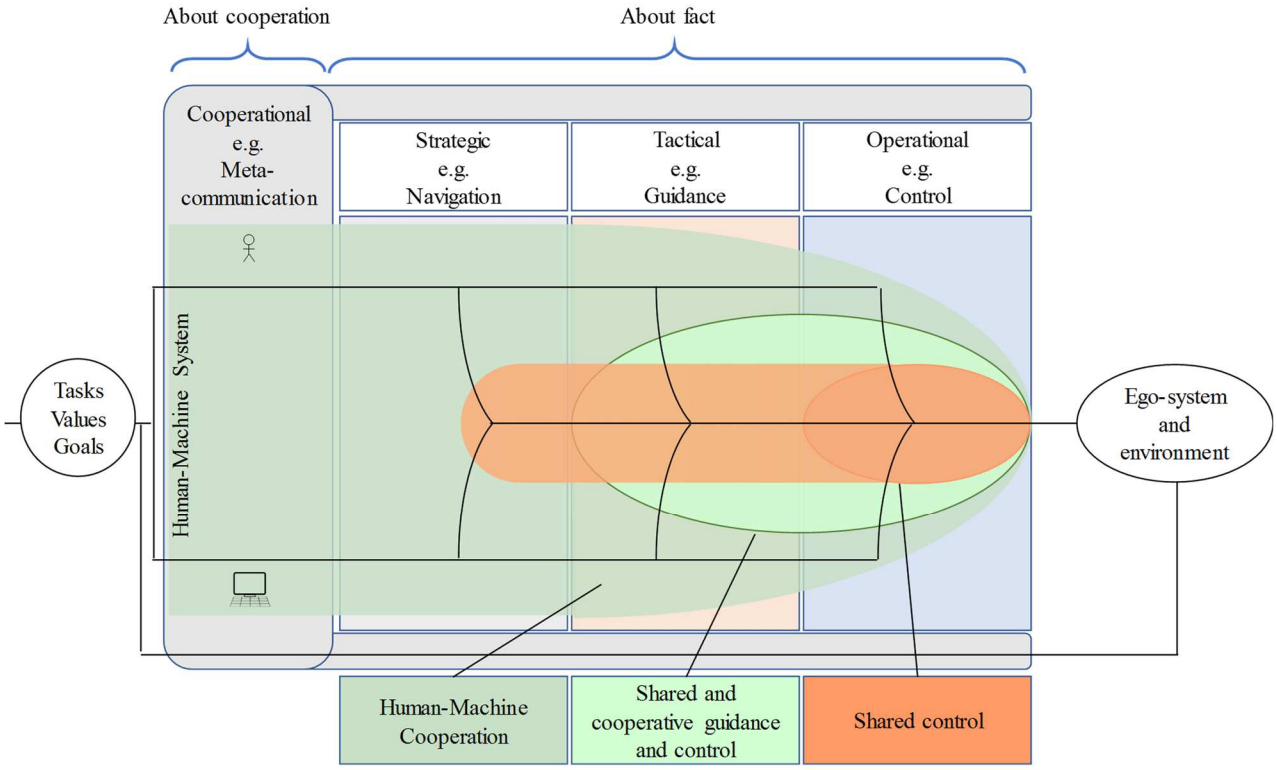

Fig. 30 The relationship between shared control, shared and cooperative guidance and control and human-machine cooperation (adapted from (F. Flemisch, Abbink, Itoh, Pacaux-Lemoine, & Weßel, 2019))

Nevertheless, as levels of cooperation were already defined as a combination of KH and KHC, the cooperation between levels presented in this part is called the layers of cooperation (Marie Pierre Pacaux-Lemoine & Flemisch, 2018). Using the model of cooperative agents' interaction, Fig. 31 shows one main link between layers, the Common Work Space.

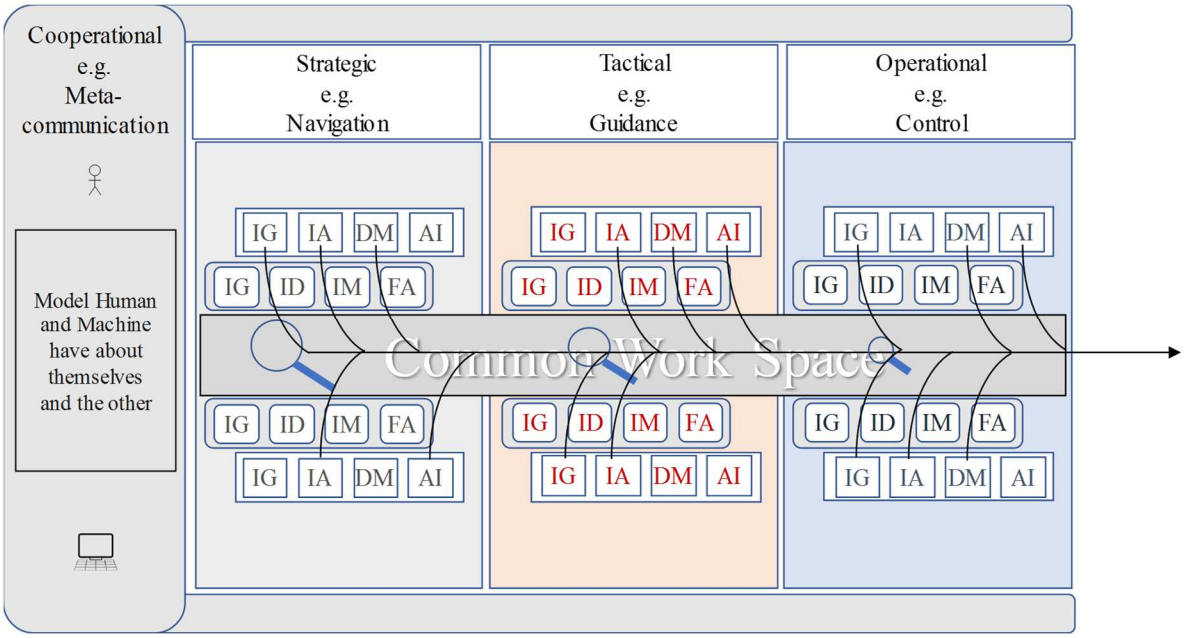

Fig. 31 Layers of cooperation

This model does not detail interaction between layers, but underlines all the possible interactions. The three CWSs, one at each level, represent in fact the same environment but with different points of view. The more activity deals with high decisional level (strategic level), the more general the information is, the wider the geographical view is. The more activity deals with short-term control level, the more information focus on specific detailed view and fast feedback.

This chapter presents the state of the art in human-machine system augmented with our contributions on Human-machine Cooperation, with a focus on how to address human factors, how to combine such human characteristics with machines that have more and more capabilities. We try to highlight benefits and risks to put together smart technologies and humans in the same environment with common goals. Several criteria, general rules and examples provides clues for designers to create cooperative assistance systems, and for managers to be careful to organize human-machine interaction in a safe, acceptable and efficient way. The next chapter aims to provide designers with tools that can help reach these objectives.

Chapter 4. Design and evaluation methods

"What we observe is not nature in itself but nature exposed to our method of questioning," *Heisenberg (1958)*

Indeed, in the description of atomic phenomena, the quantum postulate presents us with the task of developing a 'complementarity' theory the consistency of which can be judged only by weighing the possibilities of definition and observation. *Bohr N (1928). 'The Quantum Postulate and the Recent Development of Atomic Theory". Nature. 121 (3050): 580–590.*

Researchers, engineers must evaluate every new machine they design and every model that supports the design, not only the technical requirements, but also their usefulness regarding their integration in human life. That is particularly true when designers tackle human-machine systems, for all the reasons mentioned in the previous chapter. Moreover, sometimes companies and industries re-use existing machines with different objectives, or different humans, or different environments, but even if the difference is very small, it can disturb the overall human-machine system and may lead to catastrophes. Therefore, we need to use and improve tools that can support design and evaluation. These tools mainly concern experimental conditions, measurements and analysis that the designer is able to use to conduct progressive and ecological experiments. Experiment can begin from the very early stages with brainstorming and systems prototyping, to the final stages with integration in real human activities.

Methodology is not the focus of my research, but a tool I need every time I have to design and evaluate human-machine systems as a research engineer. Therefore, the chapter starts with a short state of the art about human-machine system methods, then it presents a method defined and evaluated in LAMIH. Its use during a large number of projects allowed for improving each step and tool, which are described in the following sections. Though it is not at the center of my research, the need to improve the methodology has nevertheless been made clear, thanks to lectures I have done and discussions with other researchers in human-machine system domain, and so the final section deals with such objectives.

4.1 Some methods from the literature

Methods provide useful guidelines to manage a project, from the definition of a hypothesis based on the study of objectives, to the analysis of data and results about hypothesis, and more. Deep data analysis may also lead designers to identify the justifications of the results. Several user-centered design methods aim to evaluate the ergonomics of systems. They provide knowledge about the design and evaluation of interfaces, e.g. usability and models of human-machine interaction based on cognitive behavior. Nielsen defines the usability as a sub-part of acceptability, which is the extent to which a product matches customers' expectations (Nielsen, 1993). Gould and Lewis describe usability engineering as a general approach with three strategies: taking into account of users and their tasks early on, empirical measures and iterated design (Gould & Lewis, 1985). This approach includes user aspects in most of steps of project management and defines several norms. Nevertheless, other methods exist, originating from different domains, such as the method presented in social acceptability. Brangier et al. propose a comparison between social and ergonomic approaches (Brangier, Hammes-Adelé, & Bastien, 2010). The authors underline the interest in exploiting their complementarities. This is also the method proposed by Millot, the so-called method in "U" (P. Millot, 1995). This method aims to propose an easier way to design and evaluate system than the V-cycle proposed by Royce (Royce, 1970). V-cycle, stemming from systems engineering, bases the method on the different stages of the cascade model. Nevertheless, it is very difficult to use to model complex environments, such as dynamic environments, the

main application of our research. Moreover, it does not take into account humans and their interactions with assistance systems. The method in "U" has this objective, as well as balancing human involvement with machine involvement in the control of the process in a cooperative manner.

Firstly used in telerobotic domain (Patrick Millot & Roussillon, 1991) and in Air Traffic Control (Patrick Millot & Debernard, 1993), other domains applied this method in automotive domain to design and evaluate driving assistance systems (Marie-Pierre Pacaux-Lemoine & Crévits, 2010; Tricot, Rajaonah, Popieul, & Millot, 2006). This method was also the design guide for studies in fighter aircraft domain, robotics as presented in the appendix dealing with projects done for more than 20 years, and the several domains of application.

Fig. 32 presents a new version of the method. Indeed, details about human and machine representations, their interactions through the Common Work Space, and the multi-level aspects of cooperation enrich the previous version.

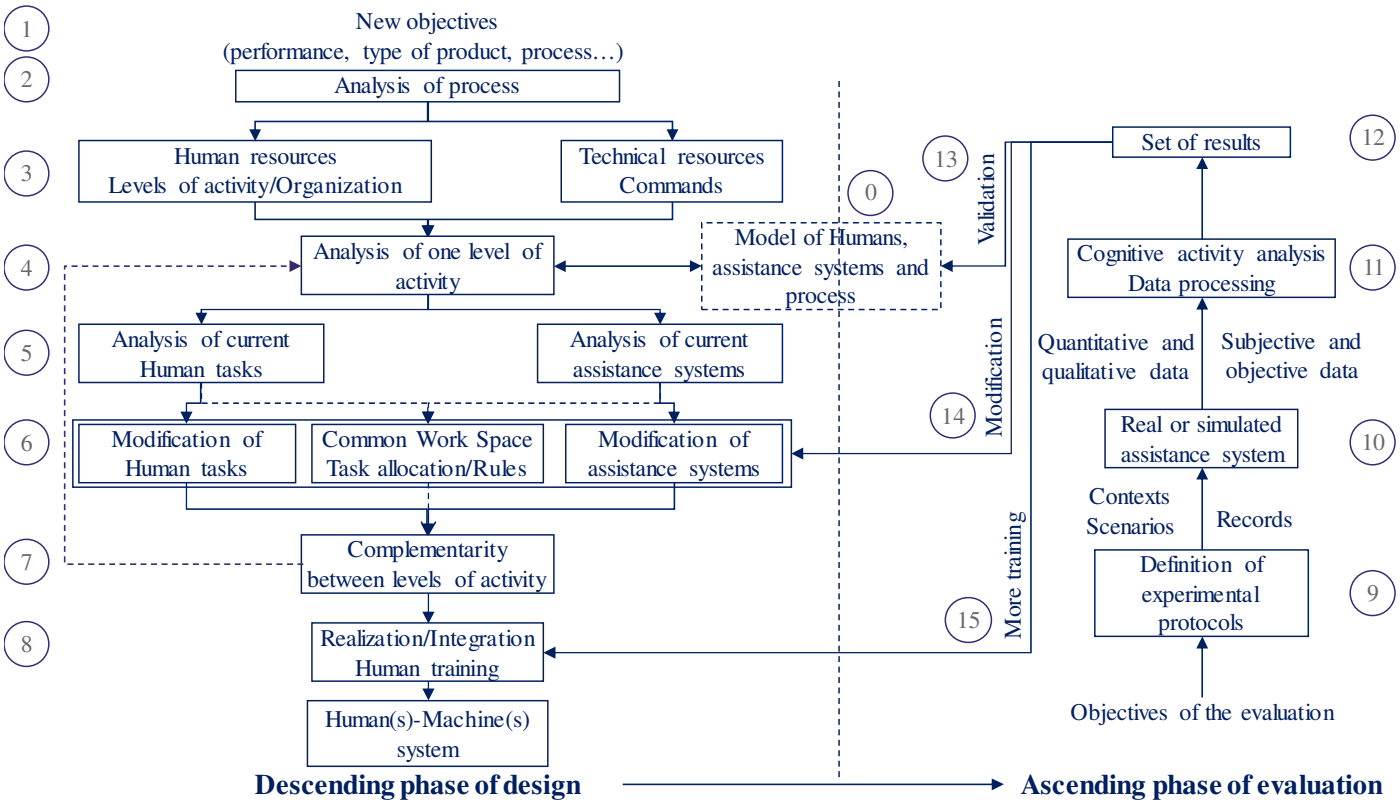

Fig. 32 Method in "U", adapted from (P. Millot, 1995)

In this method, a descending phase designs Human(s)-machine(s) system and an ascending phase evaluates it.

4.2 Descending phase for design

All the steps of the descending phase use the models of cooperative agents, organizations and cooperation presented in the previous chapter. First, designers need to know the objectives of the human-machine system they have to design (cf. Fig. 32-1). Objectives usually describe the increase of performance, but performance

is a general word that hides many things. It could be the increase of the number of planes air traffic controllers can managed, the decrease of death on the road with driving assistance systems, the increase of the number of products generated by manufacturing systems. However, performance can also mean better comfort for humans in their activities, such as for disable people. Therefore, designers must correctly identify and understand objectives with discussions with managers and experts, but it is sometimes useful to have also discussions with the future end users, especially for the next step of the method regarding the analysis of the process.

Most of the time, process and human activity dealing with the control of this process already exist. Therefore, models of current organization, models of prescribed tasks and functions, and detailed description of current process might inform designers (cf. Fig. 32-0). Less often, only human activity exists and designers have to imagine and create systems to automate parts of human tasks. Therefore, designers must identify the limits of their intervention, defined by a set of human tasks and sub-tasks they have the agreement for modification. Safety and security criteria usually define such limits. Designers study human and technical resources (cf. Fig. 32-3), and may conduct an analysis of the current process with points of view that are sometimes different from the point of view of managers (cf. Fig. 32-2). The objective here is not to avoid the influence of managers, but to have neutral approach to offer novel and original perspectives. Ergonomic and social fields help analyze human resources, extracting cognitive and physical constraints linked to activities, as well as constraints from the social organization. The method highlights the interest in extracting the levels of activity and layers of cooperation from the organization (cf. Fig. 32-4) and the models described in the section about multi-level cooperation (§3.4). The designer has to then identify tasks and sub-tasks of humans and machines at each level (operational, tactical, strategic), as well as tasks or information transferred from one level to another (cf. Fig. 32-5). At each level, the designer suggests modifications of current tasks or creations of new tasks for humans and for machines (cf. Fig. 32-6). It is an iterative procedure analyzing activity level by level, and complementarity between levels (cf. Fig. 32-7). Tasks or functions deal with individual and cooperative activities. Based on the models presented in the previous chapter (§3.2), KH and KHC functions may be analyzed through a grid to identify and define tasks and sub-tasks (cf. Fig. 33).

This grid has been used within the framework of the COCOVEA project (cf. §7.2.1, p.135). The objective was to assist car drivers with different types of Driving Assistance Systems (DAS) on the three levels of activity (operational, tactical and strategic levels) (Marie-Pierre Pacaux-Lemoine, Simon, & Popieul, 2015). The grid points out the shared and/or traded functions between human and machine (yellow part on the grid), the way human and machine can evaluate the other (respectively blue and green part on the grid) and information that should be present in the Common Work Space (pink part on the grid). In this example dealing with the automotive domain, where the human is the same for the three levels of activity (the driver), we propose to merge functions of the levels to simplify the presentation (strategic level in bold, tactical level in italics and operational level in regular font). The completion of such a grid is a difficult exercise for the designer, because each square of the grid requires an answer. For example, the question for the blue cell in the top-left of the DAS's KHC is: How does DAS able to gather information on the driver's ability to gather information for the driving task? Is it possible to use a model of this driver (their habits for example) and their current activity?

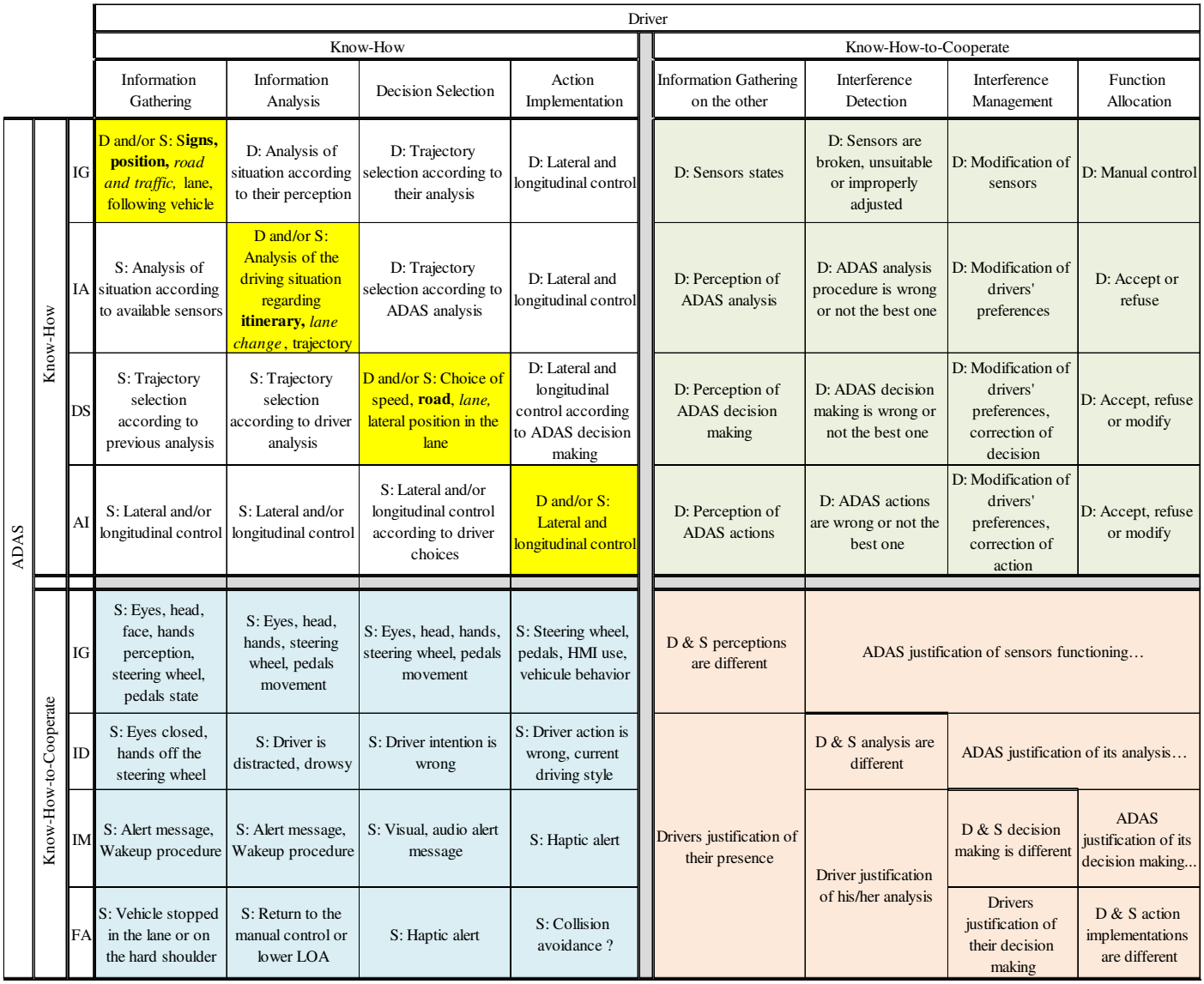

Fig. 33 Grid to identify current and future human (D: driver) and machine (S: ADAS) tasks according to their KH and KHC: example in automotive domain (KH: IG: Information Gathering, IA: Information Analysis, DS: Decision Making, AI: Action Implementation; KHC: IG: Information Gathering on the other, ID: Interference Detection, IM: Interference management, FA: Function Allocation) (Marie-Pierre Pacaux-Lemoine et al., 2015)

After checking complementarity between levels, the designer proceeds to the programming of machine functions, the programming of the interface (visual, sound, haptic…) and the training of future users (cf. Fig. 32-8). Definition and organization of human and machine functions are important in the design of a human-machine system, but the interface is another crucial part in the success of such a system. Nevertheless, we will not focus of this aspect, but use dedicated literature and especially that which aims to choose or mix different sensory perceptions (*e.g.* (Baltzer & Flemisch, 2019)).

At the end of the descending phase, the ascending phase takes over the work to evaluate the new human(s)-machine(s) system.

4.3 Ascending phase for evaluation

The ascending phase starts when the designer has identified a minimum of functions. In sociological approaches, experimenters may ask to people (in the street or on the internet) to imagine a situation and to answer to questions about the interest of a machine briefly or in detail. The advantage of this approach is that experimenters can contact many people. Nevertheless, the disadvantage is the heterogeneity of population, the strong hypothesis that people correctly imagine the situation, and the lack of details regarding the functions (Bordel et al., 2014). Another difficulty is the variety of possible answers. The synthesis work after such a survey is enormous, even if sometimes it could be fruitful as we were able to observe in the SARI project about the design of on-road driving assistance systems (cf. §7.2.2, p.137). In the engineering approach, even if we can take advantage of results from sociological approaches, we usually start the evaluation phase when the human-machine system has a minimum number of implemented functions.

The objectives of the evaluation must answer the questions raised by the stated hypothesis. What do we want to highlight with the evaluations? How can the proposed new human-machine system be assessed and prove its usefulness? Experimental procedures and protocols answer such questions (cf. Fig. 32-9).

4.3.1 Experimental protocol

Experimenters define contexts and scenarios, step 9 of the design and evaluation method (cf. Fig. 32, p.74). Context deals with whole or part of the process in which the human-machine system takes part. A starting state of the process and objectives defines a global shape of user activities. Scenarios aim to encourage users to complete some tasks by asking them (and the assistance systems) to reach goals despite triggering unexpected events. The experimental protocol may involve building several scenarios to allow experimenters to compare different experimental conditions, *i.e.* different configurations or propositions of human-machine systems, like the comparison of several levels of automation.

4.3.1.1 Scenario and experimental design

Scenarios must be different to prevent users from recognizing a situation, from making the same decisions and from interacting with the assistance system in the same way; however, scenarios require similar tasks to make the data comparable. The duration of scenario depends on the tasks and can last a few minutes for a reconnaissance mission in a fighter aircraft or for robotics activities, to several hours when the objective is to evaluate driving vigilance in automotive or industrial process supervision. Scenarios and experimental conditions are, most of the time, counterbalanced using a Graeco-Latin square experimental design to reduce order and learning effects. Such an organization of experiments defines the experimental design, which aims to reduce the impact of evaluating one type of assistance system before another one, and the specificity of a scenario according to the type of assistance system. A condition without new assistance systems defines the control condition. It makes it possible to evaluate potential benefits of the new human-machine system.

Experimental design involves defining experimental procedures, *i.e.* the various steps experimenters interact with participants taking part in experiments. Firstly, experimenters present scientific objectives and then the experimental platform. Secondly, participants may have to learn process if they are novices in the domain.

They may have to identify context and types of scenario (requested tasks), usually without using new assistance systems. Therefore, they may have to learn how the assistance system functions with a formal presentation, and then use it in a dedicated scenario to train themselves. Training scenarios are different from experimental scenarios, but with similar difficulty.

During the project with Dassault Aviation and DGA, we had the opportunity to conduct very sophisticated experiments (cf. §7.3, p.143). Fig. 34 presents an example of a task that participants had to complete for the experiments. This scenario was one of the four they had to experiment. Each experimental session was composed of five stages: mission-planning, preparation of the assistance systems (each crew member adapted the KH and KHC of the assistance systems according to their individual and cooperative needs), briefing of mission, mission completion, and debriefing (relative to the cooperative activity and to the assessment of the assistance systems). One member of the crew managed the briefing, explaining all information of the mission file following a precise order. The partner listened and spoke up if he had a different interpretation of information or requested tasks. The briefing involved the allocation of tasks between both members. After the briefing, the crew fulfilled the mission. They had two objectives of destroying, or one objective of destroying and another one recognizing, depending on the scenario.

Fig. 34 Preparation of mission in the project with DGA and Dassault Aviation (cf. details in §7.3)

4.3.1.2 Simulation of environment

Several kinds of simulators support human-machine systems studies. The level of realism can range from very low level of realism, where participants have only to perform very simple tasks but usually with many repetitions, to high level of realism where simulation only concerns environment but command and control systems are real ones. We work on these different kinds of simulators and study the impact they have on participants, and so on results.

Micro-worlds are ones of the simple simulators but they facilitate the control of many parameters of the experimental protocol (e.g. (Sauer, Wastell, Hockey, Crawshaw, & Downing, 2003)). They usually consist of one piece of software and experiments conducted on one computer with one screen. The simulation of a pasteurization plant (J. Lee & Moray, 1992), the simulation of forest firefighters (J. M. Hoc & Amalberti, 2007), the simulation of a war environment (Barber et al., 2008) are some of the well-known simulations. These kinds of simulators focus on cognitive activities and most of the time on tactical or planning level of activity. At the start of our studies on robotics, we used the Mixed Initiative eXperimental testbed (cf. Fig. 35). This environment allows the impact of levels of automation on participants' behavior to be studied. Experimenters define the number of vehicles that the human has to control when they are moving in a risky

environment, and their level of autonomy. Participants can plan vehicles trajectory and then supervise the right completion of such trajectories despite unexpected events, while they do reconnaissance (cf. §7.4.1, p.145).

This experimental environment helps to have a good level of control in the experiments but participants, who are usually novices like students (unless experiments take place in an army context), need to learn the activity as well as how to use the simulator.

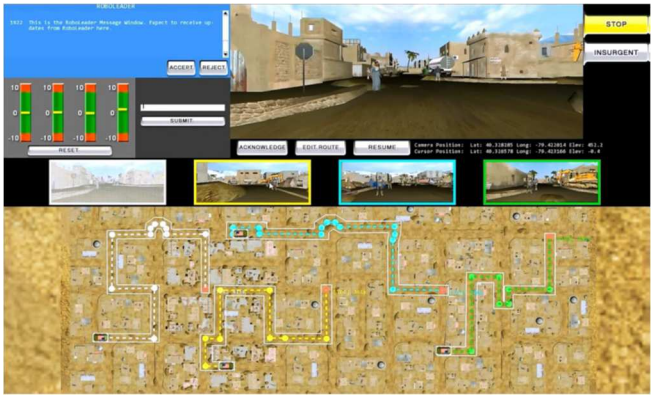

Fig. 35 MIX (The Mixed Initiative eXperimental testbed)

In a similar context, we were able to work on a more realistic micro-world and with professional participants (cf. §7.3, p.143). With the support of Dassault Aviation, we designed a flight simulator to study cooperation between the pilot and the weapon system officer, as well as cooperation between the pilot and another officer who would be in another plane and would have more planning functions. Several types of systems to support cooperation were studied. In this experiment, tasks were the usual ones that officers learned from training and experience, but we simulated the environment. Even if such officers were used to training themselves with high fidelity fighter aircraft simulator, they were fully involved in our experiments. We were working on future displays of Rafale and they were pleased to participate to such experiments (M P Pacaux-Lemoine & Loiselet, 2002). The place where we conducted experiment is another important point that made these experiments successful. Indeed, we stayed for several weeks in air bases close to officers' operating and break rooms. We were at their disposal to explain the experiments and to find dates to conduct them.

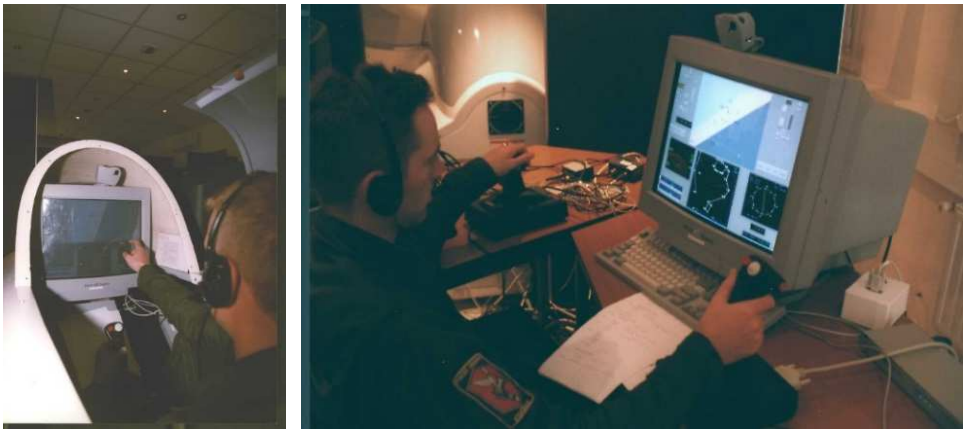

Fig. 36 Workstations of pilot and weapon system officer

The more advanced simulators we used were the car driving simulators of University Polytechnique Hauts-de-France (UPHF) (cf. §7.2.1, p.135), IFSTTAR (7.2.2, p.137) and Renault (cf. §7.2.4, p.141). Participants, whether they are beginners or more experienced drivers, understand the driving tasks and can easily complete them, especially in a reference situation without new devices or assistance systems. With such simulators, participants drive the car as if it is a rented car (unless they have the same car). Therefore, the main difference is the driving environment. Nevertheless, it is now possible to design very realistic environments based on real topographic layout, lane widths, road markings, sight distances, and other geometrical characteristics such as trees, houses of the field.

Fig. 37 Driving simulators of IFSTTAR (a static one on left), UPHF-LAMIH (a mobile one) and Renault (mobile one on the right)

In the SARI project (§7.2.2, p.137), we were able to find similar driving behaviors (risky position in a lane on a vertical curve) between participants who drove with one of the two kinds of driving simulator (UPHF and IFSTTAR), and drivers who used the real road but were not aware that their driving data was being recorded (Auberlet, Pacaux, Anceaux, Plainchault, & Rosey, 2010; Auberlet et al., 2012).

A simulated environment proves to be a very useful tool for experimenters to control experiments. Nevertheless, participants may sometimes display unnatural behavior, since they are aware their activities are being recorded and do their best to meet experimenters' expectations. When we conducted experiments during the ST2 project (cf. §7.2.3, p.139), with the objective of studying drivers' behavior during risky situations and their ability to anticipate such situations, we observed that participants needed about 20 minutes to find their normal, comfortable driving position (Hault-Dubrulle, Robache, Drazétic, & Morvan, 2009; Hault-Dubrulle, Robache, Pacaux, & Morvan, 2011), even if the car was a real one (cf. Fig. 38). In this experiment, several types of data such as biomechanical, physiological, psychological data, drivers' actions, all synchronized, support deep analysis (Robache, 2017).

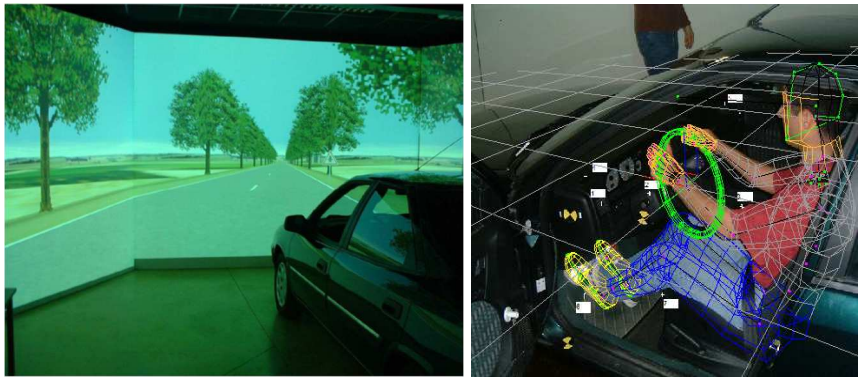

Fig. 38 Car driving simulator of the University of Valenciennes (static version) and digital anthropometric model

For each stage of the experiments, designers and experimenters prepare data records. Data can be objective, subjective, qualitative, quantitative, raw, interpreted, and coded, depending on experimental design and experimental platform. Data record definition and control are an important step for experimenters since it is a necessary condition for obtaining useable data to generate significant results. The next section deals with this step.

4.3.2 Data records

Data is a more frequently cited word nowadays, as in, for example, big data, database, data mining, data cloud, but experimenters must find the right compromise between recording many data and spending a lot of time cleaning, selecting and analyzing data, or selecting the most appropriate data and the way to analyze them. The following sections present some recommendations to reach such good compromise.

4.3.2.1 Online data records in a simulated environment

Online data records and their analysis are at the core of the understanding of human-machine system activities. Recorded data must highlight the states of the human, the assistance system and the process, as well as transitions between such states. Designers can program data records directly on the experimental platform.

All commands sent through human-machine interfaces and information updates in the Common Work Space constitute precious information for experimenters to understand process situations and agents' decision making regarding such situations. Precoding data during execution of simulation and experiments may support analysis. During the experiments we conducted in most projects, we used the model of the cooperative agent to code agents' individual and cooperative activities. An example of coding and use of the coding is presented in section §4.3.4. Even if it is difficult to anticipate all human reactions, precoding provides a strong basis which is then improved by offline data. Of course, coding assistance system activities is easier than human activity since it is the output of a technical agent program. Programed information from scenarios, and especially events, can also provide interesting data to identify process situations.

Fig. 39 Confrontation of pilots and weapon system officers to the video recording of their mission

Spontaneous verbal reports and video outputs of user workstations provide other types of data. Spontaneous verbal reports are especially interesting when two humans work together during experiments. That was the case in the experiments conducted in air traffic control (cf. §7.1, p.132) and in fighting aircraft control (cf. §7.3, p.143). Professional human operators, like radar and planning controllers, or pilots and weapon systems

officers, train themselves for their individual tasks, but also for cooperation. They are usually used to working with the same partners. Therefore, verbal reports are full of information about individual and mutual information processing. That was especially the case when humans had to perceive or transmit all information through electronic devices, because they have to be silent to avoid detection by the enemy for example. Online verbal reports are sometimes not easy to understand for experimenters. Therefore, in addition to these reports, experimenters use self-observation reports. After task execution, participants watch video records of their activities and provide comments to explain (but not justify) their decision making.

Like in spontaneous verbal reports, simulated environments give experimenters the opportunity to record other kinds of subjective viewpoints, *e.g.* online participants' workload and situation awareness. Experimenters evaluate online workload assessment by asking to participants to regularly answer questions requesting information about their workload. Questions are verbal or posed by the way of a scale drawn on a display (cf. Fig. 40). Even though it is an additional task for participants, this question can be part of a cooperative task, especially if participants have to evaluate their own workload to decide to allocate tasks to a partner. We used this method during experiments conducted with air traffic controllers. The radar controller evaluated their own workload, while the planning controller evaluated the workload of the radar controller. The objective was to know if the planning controller was able to evaluate the workload of their partner in order to allocate task to the assistance system if they were overloaded (cf. §7.1, p.132). Results confirmed this hypothesis and advocated studying multi-level cooperation (cf. §3.4).

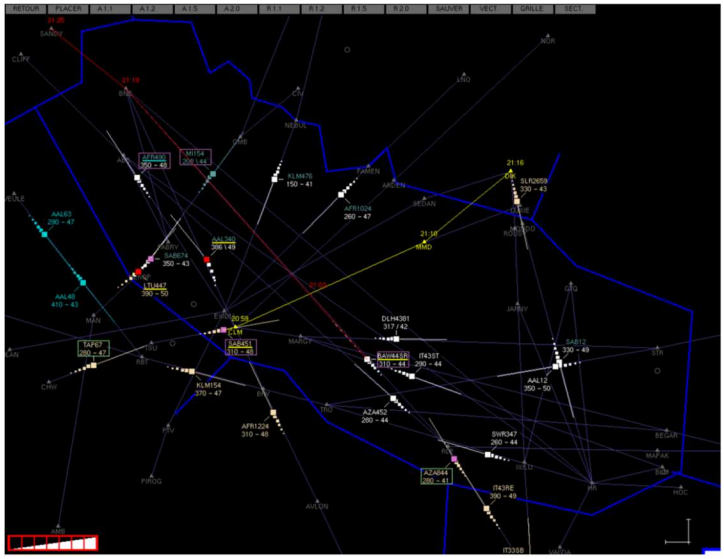

Fig. 40 Workload assessment on the radar display of air traffic controllers work position (red scale on the left lower part of the interface)

Designers and experimenters may compare the evaluation of workload done by participants to calculated assessment performed by the system using different technics. In the experiment conducted with air traffic controllers, a scheduling module based on three sub-modules (task set prediction, characterization of predicted set of tasks, partitioning) focusing on the radar controller's KH, decided allocation of shareable tasks to the assistance system (cf. §7.1, p.132). This ability of the schedule module was in fact the KHC of the assistance system that is able to predict human workload through the model of them that it builds (Jean-Michel Hoc & Lemoine, 1998b).

The evaluation of situation awareness is also a useful tool to state how participants perceive and understand a process or an environment, and come to a decision. Several methods exist. Endsley proposed a method associated with her three-level model of SA (Endsley, 1995a)(cf. §2.3.1, p.43). The method, known as SAGAT (Situation Awareness Global Assessment Technique), used in simulated environments, consists in freezing the situation randomly, blanking the displays and asking participants relevant questions on their understanding of the current situation. This method compares participants' perception, understanding and projection to those of a Subject Matter Expert (SME) who also follows the same procedure, but without blanked displays. Endsley validated SAGAT experimentally in a set of air-to-air engagements, played on a flight simulator. Indeed, the questions are so dependent on the situation that participants are unable to answer if they are not aware of that situation. SAGAT has acquired a status as a reference method. However, its main limitation lies in the freezing of the simulation, which prevents its use in real applications. During experiments conducted in robotics (cf. §7.4.3, p.150), we used an adapted method to evaluate participants' situation awareness. Among the tasks they had to complete, participants had to provide information about their situation awareness during the experiment. However, reconnaissance was one of the tasks they had to perform, so that was not an additional task requested only for data records. Fig. 41 provides an example of the electronic fulfilment of an interface displaying available information (walls, robots position and trajectory). Participants had to add information about what they perceive in this environment (victims and different types of signs).

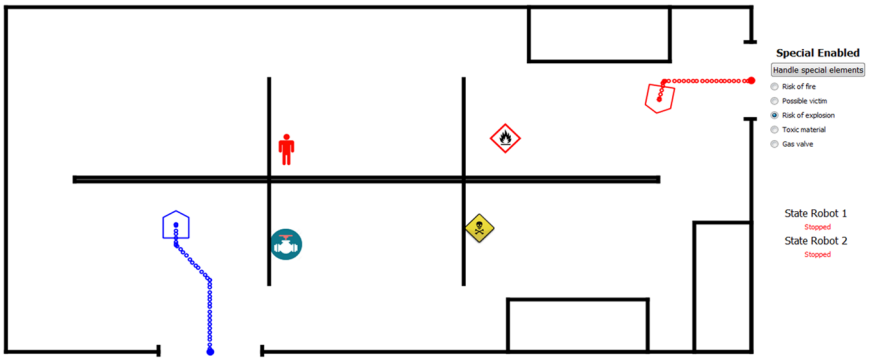

Fig. 41 Participants' situation awareness during experiments conducted about human-robots cooperation (L. Habib, Pacaux-Lemoine, & Millot, 2017a)

Simulated environments allow testing assistance systems in safe and controlled conditions. Such experiments are required before conducted tests in real world. Nevertheless, real world tests involve many constraints presented in the following sections.

4.3.2.2 Online data records in a real world

Experiments conducted in the real world are much more complex and much less controllable than in simulated environments, especially when the focus is on human-machine cooperation. Two experiments conducted in car driving and in robotics brought our attention to such difficulties. The first one deals with experiments in car driving to evaluate impacts of dynamic and adapted road signs on car drivers' behavior (cf. §7.2.2, p.137). The second one deals with human-robot cooperation in reconnaissance missions (cf. §7.4.2, p.147).

First at all, such types of experiments involve requesting various agreements from different institutes, especially to guaranty the safety of participants and to respect existing rules in the domain. These procedures can take several months, so experimenters must anticipate this.

In the first experiment about the study of car drivers' behavior, experimenters designed assistance systems, as well as systems to record data. Fig. 42 presents the set-up of experiments to evaluate the impact of two dynamic road signs, which repeat previous road signs when the speed of the car does not decrease on the second measurement (reminder) and on the third measurement (slow down). Experimenters recorded speeds of each car during several half days, as well as two video recording of each car. Video recordings supported the analysis of drivers' behavior, such as the position of the car in the lane and the use of the brake pedal (brake lights). The measurement systems were not visible. The objective was to prevent their detection by drivers who may make connection with policy control. RTMaps software supports synchronization between all data as well as data records (cf. §4.3.4, p.93, Fig. 54), (Gruyer, Royère, Du Lac, Michel, & Blosseville, 2006). Experiments observed about 1000 vehicles per day. Therefore, the data were more quantitative than qualitative. However, we were able to stop some drivers after traveling across the experimental road, and for a portion of the drivers, we were able to synchronize quantitative and qualitative data (Auberlet et al., 2012; Bordel et al., 2014).

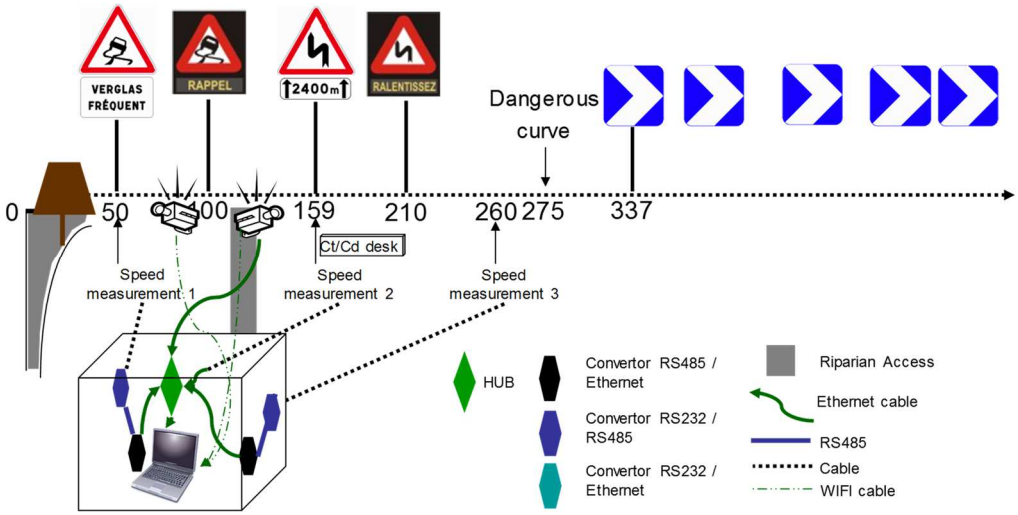

Fig. 42 Data records during experiments conducted on real roads

In the second experiment conducted within the framework of the TAROT project (cf. §7.4.2, p.147), participants were professional teleoperators of the French army. They had to supervise and/or control a robot moving in an environment with many obstacles like stones, bushes and holes in the ground. This environment, the ruin of an abandoned factory, increased the attention of participants who knew that robot might not be able to detect some of these obstacles. Moreover, unlike controlled simulated environments, technical problems occurred like communication disturbances or interruptions. Even if such problems can also occur during real missions, these uncontrolled events prevented repetitive scenarios from being conducted to extract statistically significant results. Therefore, due to the difficulty and the risks of completing the tasks with an expensive prototype robot, experimenters remained in contact with participants by radio. Participants regularly checked their decision making with experimenters. Even if such an experimental method distorted results, verbal reports were rich regarding the understandability of the robot and its cooperativeness. Unlike the experiments presented previously, results were more qualitative than quantitative, and more subjective than objective.

Fig. 43 Experimental environment to study human-robot cooperation in reconnaissance mission

Evaluating workload and situation awareness in a real environment is of course more problematic than on a simulator, unless evaluating their workload and awareness are part of participants' tasks. Concerning workload assessment, Durso et al. proposed an over-the-shoulder subjective assessment by a subject matter expert (SME)(Durso et al., 1998). They also used a query technique that did not have a memory component, SPAM (Situation Present Assessment Method). The measurement consists in experimenters' detecting participants' errors concerning specific events integrated into the scenarios. Regarding situation awareness assessment in real situations, Jones and Endsley proposed the "real time probes" method. It consists in asking a series of periodic questions related to the three SA levels (but without blanking the displays) and using participants' response time to the questions as a complementary index of the SA quality. They partly validated the method by making comparisons with SAGAT (D. G. Jones & Endsley, 2004).

Online records provide objective and subjective data that reflect human and technical agents' activities. Focusing on their tasks, humans normally had no time to reconstruct their understanding of situation, or to imagine more than what they actually remembered doing during the experiments. However, they prevent experimenters from going deeper into the analysis to understand reasons for participants' behavior. Offline records can mitigate such shortfalls, and various methods help aggregate online and offline data. The following sections detail these capabilities.

4.3.2.3 Offline data records

After the end of each experimental session, experimenters can again assess workload and situation awareness, however questionnaires constitute the main tool for the offline records.

One of the main methods to evaluate participants' workload is NASA TLX (Task Load indeX). This method poses questions to participants in two phases (Hart S. G. & Staveland L. E., 1988). After each experimental session or each experimental condition, experimenters ask participants to give their feelings about six descriptors by drawing a cross on a 10cm line. Descriptors are mental demand, physical demand, temporal demand, own performance, effort and frustration level (cf. Fig. 44).

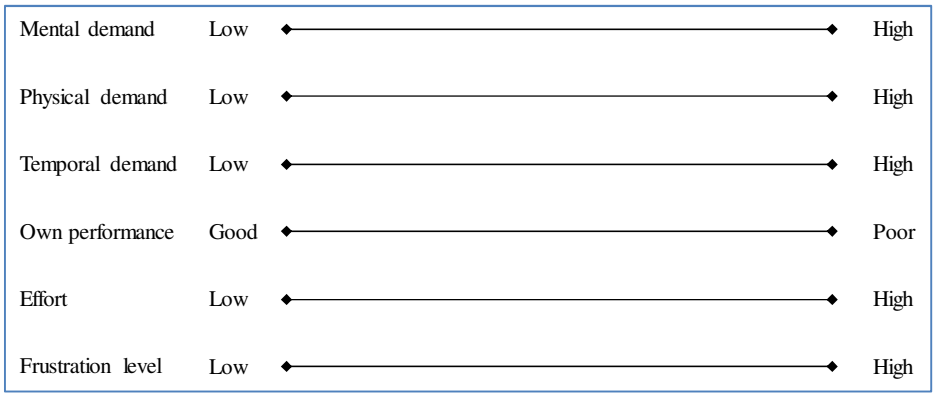

Fig. 44 Descriptors of NASA TLX

Participants then specify between two descriptors which one is the most important for them when they complete tasks (cf. Fig. 45). These selections define a weight for each descriptor.

Physical demand / Mental demand	Temporal demand / Physical demand	Temporal demand / Frustration level
Temporal demand / Mental demand	Own performance / Physical demand	Temporal demand / Effort
Own performance / Mental demand	Frustration level / Physical demand	Own performance / Frustration level
Frustration level / Mental demand	Effort / Physical demand	Own performance / Effort
Effort / Mental demand	Temporal demand / Own performance	Effort / Frustration level

Fig. 45 Selection of descriptors according to importance perceived by participants

After these two steps, experimenters calculate the workload for each participant for each experimental condition using the formula presented on the equation 1.

$$WL = \sum_{n=1}^{6} (\alpha_n * R_n)$$

Equation 1: Workload calculation according to descriptors “R” and their weight “α”

We used this method for several experiments and we found that it could be useful with participants who are professional human operators, like air traffic controllers, aircraft pilots, teleoperators of robots. Indeed, they give a good representation of their work and tasks, and they are used to evaluating themselves with similar questions, especially when they perform risky tasks. However, these questions are too difficult for non-professional human operators like drivers or students.

Nevertheless, questionnaires remain the main tool we use to evaluate the quality of the interaction between participants and assistance systems, but also how participants perceive experiments, the experimental environment, procedures and evaluations. For experiments conducted in the automotive domain, we designed specific questionnaires with the help of colleagues who are experts in psychology. However, in order to have a generic questionnaire dealing with human-machine cooperation, we proposed to use the model of a cooperative agent to deduce questions. The grid presented in Fig. 33, and summarized by Fig. 46 may support the proposition of questions.

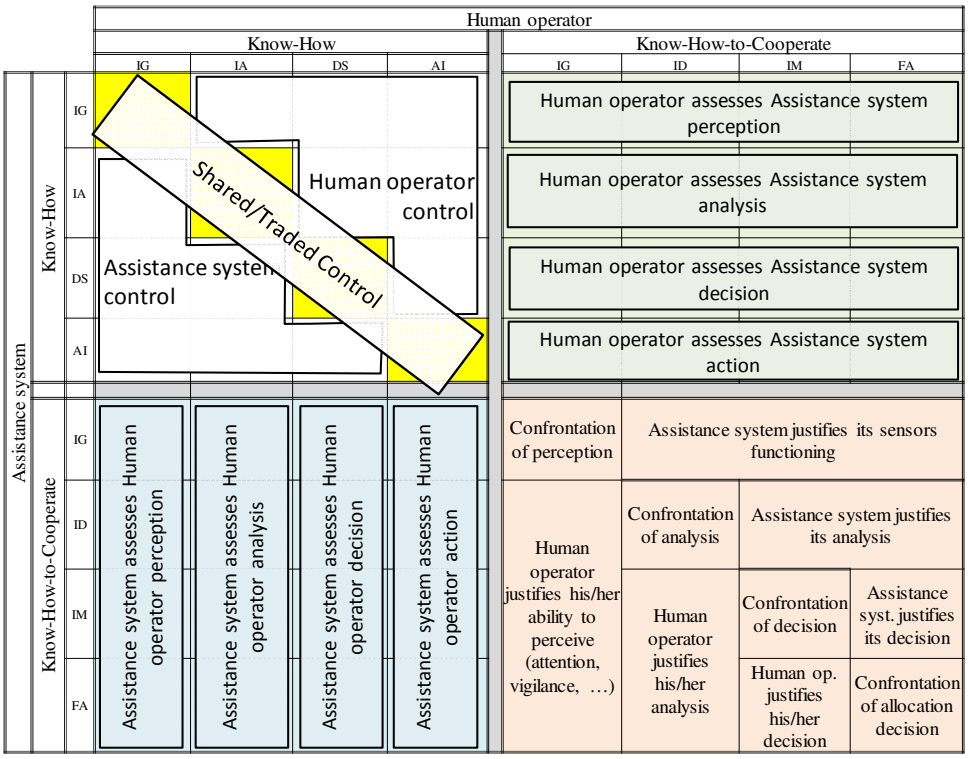

Fig. 46 Grid based on the cooperative agent model, a tool for design and evaluation of human-machine cooperation (IG: Information Gathering, IA: Information Analysis, DS: Decision Selection, AI: Action Implementation)

In the case of the study of cooperation between driver and ADAS, participants answer by drawing a cross on a 10cm line, from low to high, in response to the following questions. The questions address participants feelings regarding their own KH, KH and KHC of assistant system. Each square of the grid on Fig. 46 can be associated to a question. Some examples are provided below:

- To what extent do you think the assistance system is able to perceive the situation?
- To what extent do you think the assistance system is able to make a good decision?
- To what extent do you think you are able to detect conflict with the assistance system (decision, action…)?
- To what extent do you feel in control of the assistance system?
- To what extent do you think the assistance system is able to evaluate your decision making?
- To what extent do you think the assistance system is able to manage conflicts with your activity?
- To what extent do you think the assistance system is able to manage authority?
- To what extent do you think you can negotiate with the assistance system?

As a conclusion for this section, we can write that experimenters have to adapt data recordings according to type of experimental environment (real vs. simulated), type of participants (professional vs. non-professional) and type of assistance system (very simple vs. complex or complicated one able to complete the four functions of the KH and the four functions of the KHC). The next section deals with the presentation of iterative and gradual ways to evaluate several states of development of the assistance system (maturity), as well as its effectiveness and resilience according to unexpected events of the process or the environment.

4.3.3 Assistance systems implementation

The way assistance systems are implemented in the real or simulated experimental environment constitutes the 10th step of the design and evaluation method (cf. Fig. 32, p. 74). In system engineering, designers are used to testing assistance systems in terms of their operating envelope, their robustness and technical performances. They usually refer to TRL (Technological Readiness Level). They use a typical numerical database or randomized data for assistance systems to be independent of inputs, such as input from a human operator. However, sometimes, participants have "a particular ability" for finding breaches in assistance system functioning and crashing it. Therefore, such technical tests are, of course, necessary, but tests of usability and acceptability must be the next steps. Boy deals with technology maturity, maturity of practice (at the individual level), and organizational maturity (Guy André Boy, 2018). Therefore, assistance systems can be evaluated at different levels and for different kinds of maturity. The following sections provide details about such steps and their complementarity. The descending phase of HMS design provides functions that human and technical agents have to perform to reach objectives. Designers may fully program these functions in order to test them with human participants. Nevertheless, experimenters may face several technical problems that may disturb scenarios they had prepared. Moreover, even if participants do not find breaches in the systems, some of them may be able to anticipate events that experimenters hoped were unpredictable. Several experimental techniques make it possible to avoid, or at least mitigate such problems.

The authors proposed the theater-system technique, which consists in letting both designer and participant share the same experimental environment (Schieben, Heesen, Schindler, Kelsch, & Flemisch, 2009). Each has a similar workstation that can communicate with the others, and participants can comment or answer experimenter's questions when they are modifying assistance systems. This technique is useful when designers want to adapt an assistance system to participants. However, there is a risk of having too many individual differences between participants and not being able to design a system suitable for several human characteristics. The following techniques focus on experimental design. The first one deals with online control of scenarios in order to avoid the problems mentioned above. The second technique explains how it is possible to simulate an assistance system.

4.3.3.1 Online control of scenario

We felt the need to have an online control of the scenario when we had to conduct experiments in the automotive domain to evaluate cooperation between drivers and ADAS. We carried out two main improvements to the UPHF driving simulator by adding a module that gave us the ability to have a bird eye's view of traffic around the ego car, *i.e.* the car driven by the participant. The driving simulator software supported the definition of scenario according to number of cars, their type, speed and running time. However, it was not possible to modify traffic during experiments to adapt the scenario to participants' behavior. Therefore, we added a second module to be able to select a car in the traffic and to control it through a specific interface. This new module aims to remotely control the selected car (steering wheel at the right of the experimenter on Fig. 47), or to select predefined rules for this car to have specific behavior (Marie-Pierre Pacaux-Lemoine, Simon, & Popieul, 2003). These new modules helped conduct experiments in the two projects, ST2 and ARCOS (cf. §7.2.1, p.135). However, today the driving simulator software, based on SCANeR (software of OKTAL Company) offers such abilities in the latest version.

Fig. 47 Control room of UPHF's car driving simulator

4.3.3.2 Online control of assistance systems

In a research domain like the study of Human-Machine Cooperation, it would be useful to evaluate concepts of assistance systems (*i.e.* their main rules) in order to know if it would be interesting to design and program such types of assistance systems. How many designers programmed and implemented systems that were never used? We had the objective of simulating an assistance system when we proposed new assistance systems to fighter aircraft crews. We used the Wizard of Oz techniques, based on the children's story from 1900, in which the wizard of the wonderful land of Oz is an impostor, because he used trickery to give the illusion of power. Therefore, with these techniques, experimenters are temporally the "imposters". Indeed, they act as if assistance systems are completely programmed systems, and so participants believe they are fully implemented.

In the project about the domain of fighting aircraft, we had to simulate several assistance systems (cf. §7.3, p.143). Two experimenters had to simulate two types of tactical assistance systems and voice recognition (M P Pacaux-Lemoine & Loiselet, 2002), *i.e.* KH and KHC of assistance systems. Three workplaces made up the experimental environment: one for the pilot, one for the weapon system officer and one for experimenters who controlled experiments and simulated the assistance systems (cf. Fig. 48).

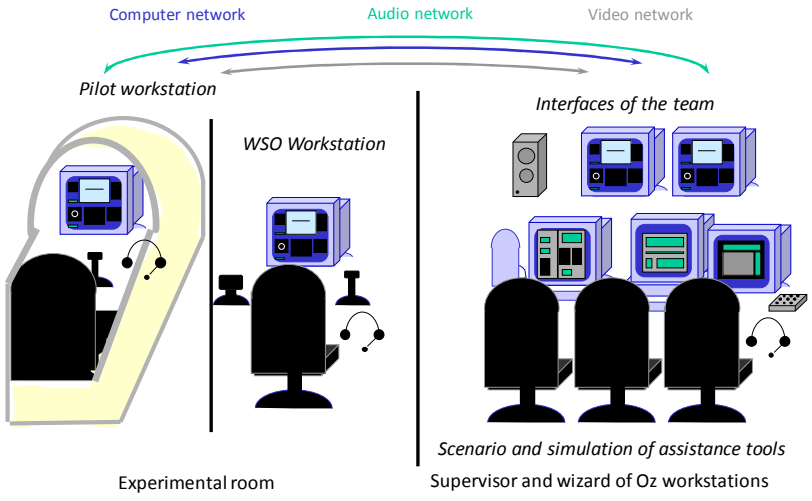

Fig. 48 Wizard of Oz platform to conduct experiments with fighter aircraft crews

Designers only programmed the KHC of the assistance systems (visual display for communication, analysis of the current participants' tasks for mutual control). They also had to program specific tools to simulate their KH (analysis of mission, updating information about missions) (cf. Fig. 49).

Fig. 49 Workstations to control experiments and play Wizard of Oz roles

We conducted a similar type of experiment in robotics domain with the TAROT project (cf. §7.4.2, p.147). Experimenters simulated assistance systems in the first phase of the project, but tested programmed assistance systems in the second phase. Designers programmed assistance systems according to results stemming from experiments conducted in the first phase. Experimenters simulated the KH of the ground robot. First, a hidden experimenter (number 1 in Fig. 50) simulated, with teleoperation, the operational KH to move between two points using algorithms like edge and object tracking, and obstacle avoidance. This experimenter was also in charge of robot safety.

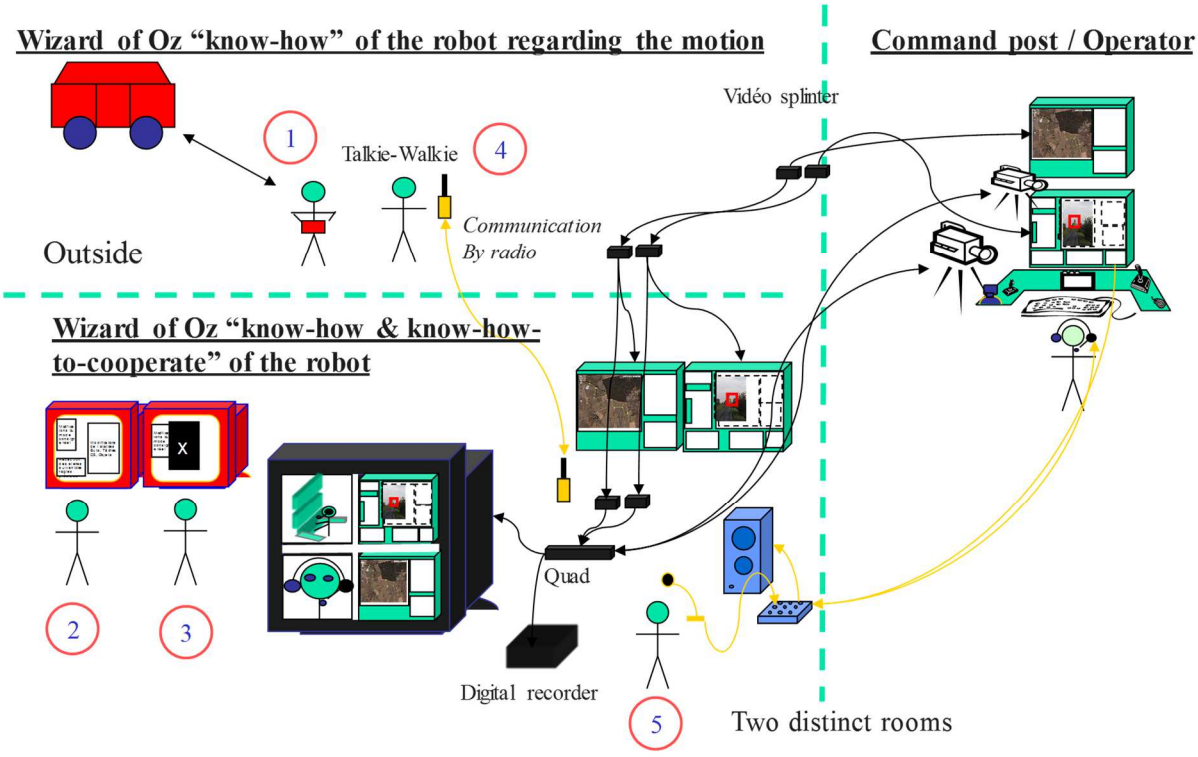

Fig. 50 Wizard of Oz platform for experiments in robotics

Experimenters 2 and 3 in Fig. 50 simulated respectively updating a tactical assistance system with the mission (KH of robot to complete mission at the tactical level), messages from assistance system to participant (KHC of robot), and feedback about edge/object tracking (KHC of robot at the operational level). This experiment split experimenters into two areas. Therefore, two more experimenters were necessary to orchestrate scenarios (experimenters 4 and 5 in Fig. 50). We had to write scripts for each experimenter in order to synchronize their activities, and to be sure they repeated same behavior for each task and each participant (cf. Fig. 51).

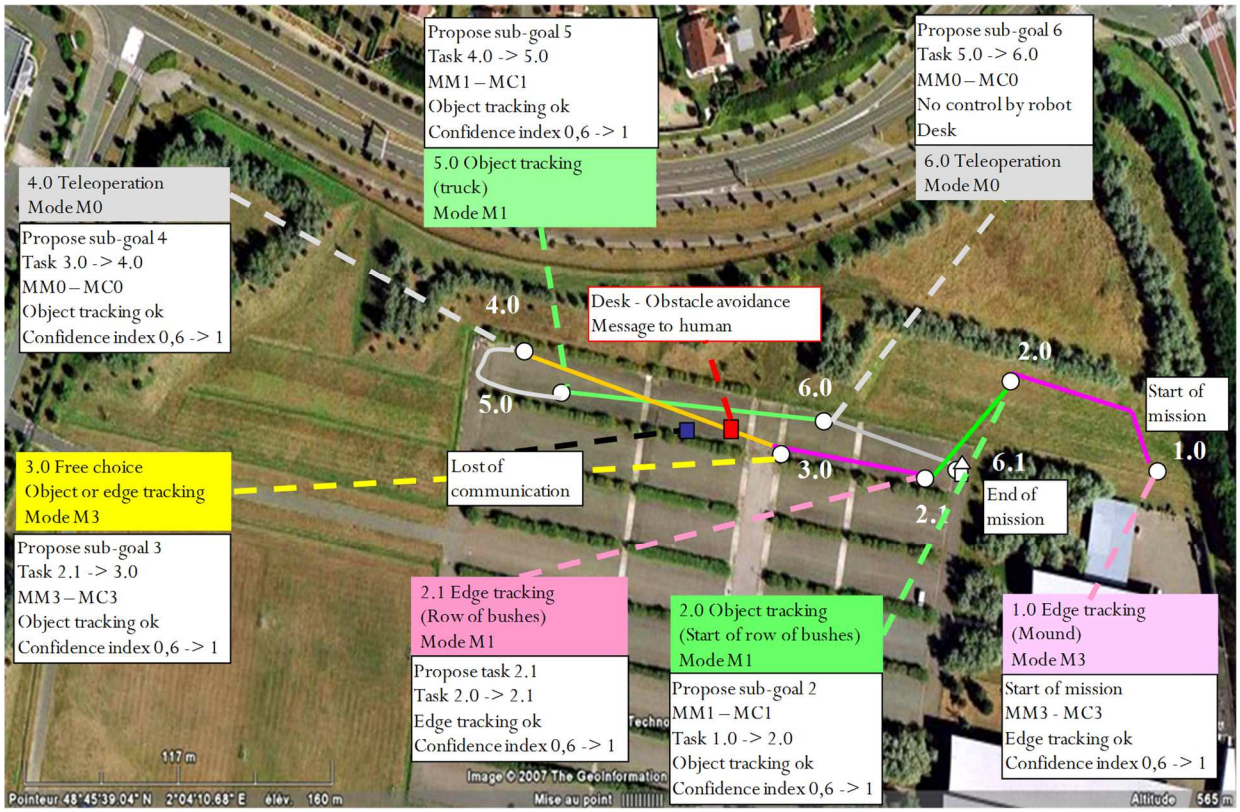

Fig. 51 Example of script for experimenters who play the Wizard of Oz role for the tactical assistance system (experimenter 2 on Fig. 50)

This section dealt with implementation of assistance systems within the experimental framework with scenario. Thanks to the implementation or simulation of assistance systems in the experimental environment, experimenters and participants can conduct experiments. Predefined data recordings provide a lot of information about several aspects of the human-machine system. The following section deals with data processing and especially the tools we designed to take advantage of all the types of data, online/offline, objective/subjective, quantitative/qualitative data.

4.3.4 Data processing

Data processing is the 11th step of the method (cf. Fig. 32, p.74). Many methods exist to analyze data, e.g. factorial analysis, data mining. However, few methods exist that are able to confront subjective, objective, quantitative and qualitative data. Moreover, few methods help experimenters to understand data and provide explanations or justification of results. The model of a cooperative agent may support such an analysis. The idea is to use the coding of agents' activity done according the model of cooperation to highlight interactions

between agents. We did such work to analyze experiments conducted in the air traffic control (cf. §7.1, p.132), and in the automotive domain (cf. §7.2.1, p.135), as well as in the robotics domain (cf. §7.4.2, p.147).

Fig. 52 provides an example of the coding of the individual and cooperative activities of radar and planning air traffic controllers. MAC SHAPA was the software we used (Sanderson et al., 1994). On the third column ("VERB-SIM") are displayed the online verbalizations of both controllers ("CR:" and "CO:": the French acronyms for radar and planning controller respectively). On the fourth and fifth column, the coding of controllers' activities based on what they did through their interfaces (commands or other information to provide to the other controller), or on what they said during experiments, the online verbalization ("ACTIVITE-CR" and ACTIVITE-CO", the French acronyms for the activities of radar and planning controllers respectively).

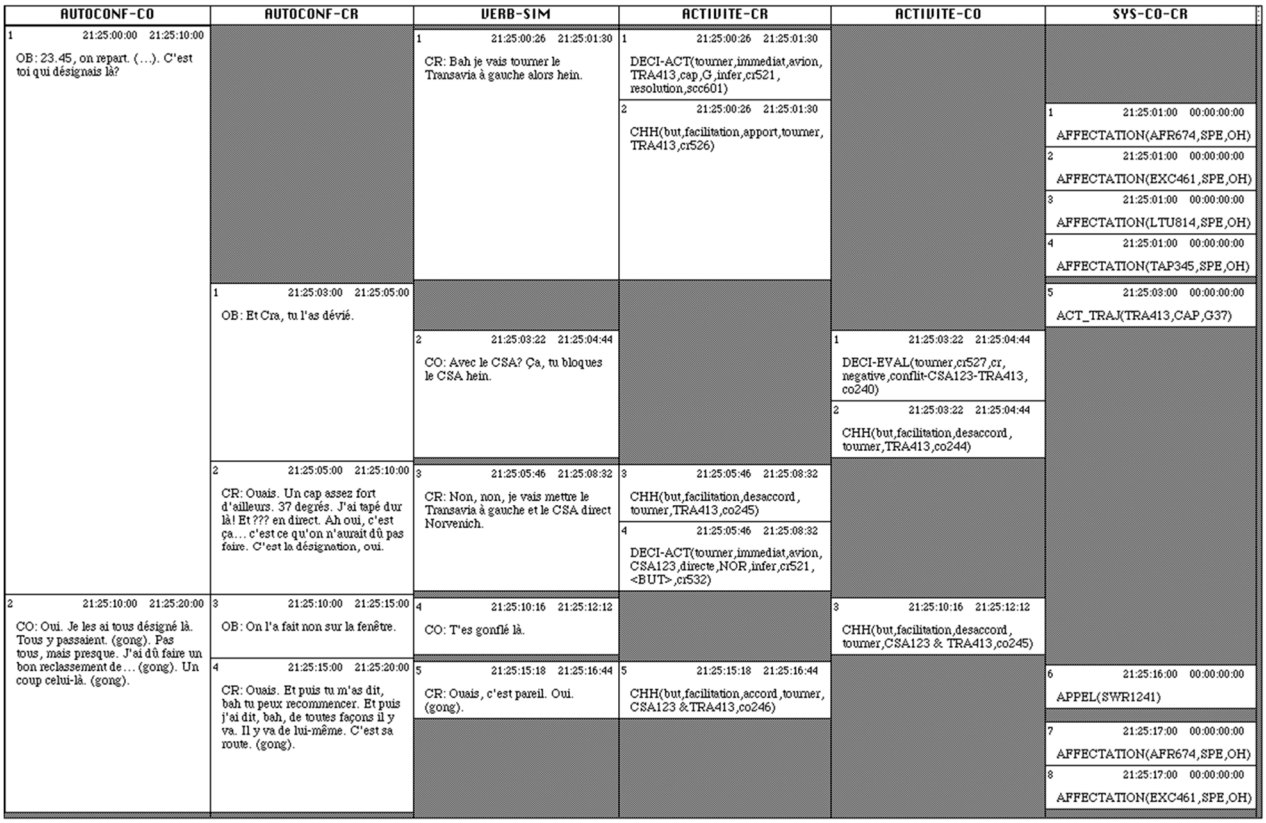

Fig. 52 Example of use of MAC SHAPA software

The last column coded the activity of the assistance systems ("SYS-CO-CR": French acronym system for planning controller and radar controller). We used the same coding for human and technical agents, and we detailed main functions of KH and KHC with predicates and attributes identified during the coding. We were two coders, we shared works between both, but each coder controlled the work of the other in order to have the same way of coding (update of predicates and attributes) and to modify coding if necessary. The two first columns dealt with verbalizations from self-confrontation of controllers ("AUTOCONF-CO" and "AUTOCONF-CR": French acronym for respectively self-confrontation of planning controller and radar controller). They did not have to justify themselves, but explain why they made some decisions. These columns usually supported the coding when online verbalizations were not enough explicit. The software synchronizes cells on each column according to time code records. The latest versions of MAC SHAPA allow all data to be synchronized with video records.

With the help of projects for engineers and master's students, we programmed a piece of software on similar principles as Mac SHAPA, but adapted to allow synchronization with the driving simulator of UPHF during the ST2 project (cf. Fig. 53) (cf. §7.2.1, p.135).

Fig. 53 Software designed to code drivers and assistance systems activities

We tried to reach the same objective with a piece of software we designed using RTMaps environment, when we conducted experiments during the SARI project. During this project, we had to conduct experiments in the real world, directly on the road. As explained in section 4.3.2.2, we needed to put hidden sensors in the road and cameras at several places, in order to record cars and drivers behaviors in specific situations, with or without assistance systems (dynamic signs). The software designed supported the synchronization of quantitative and qualitative data (cf. Fig. 54).

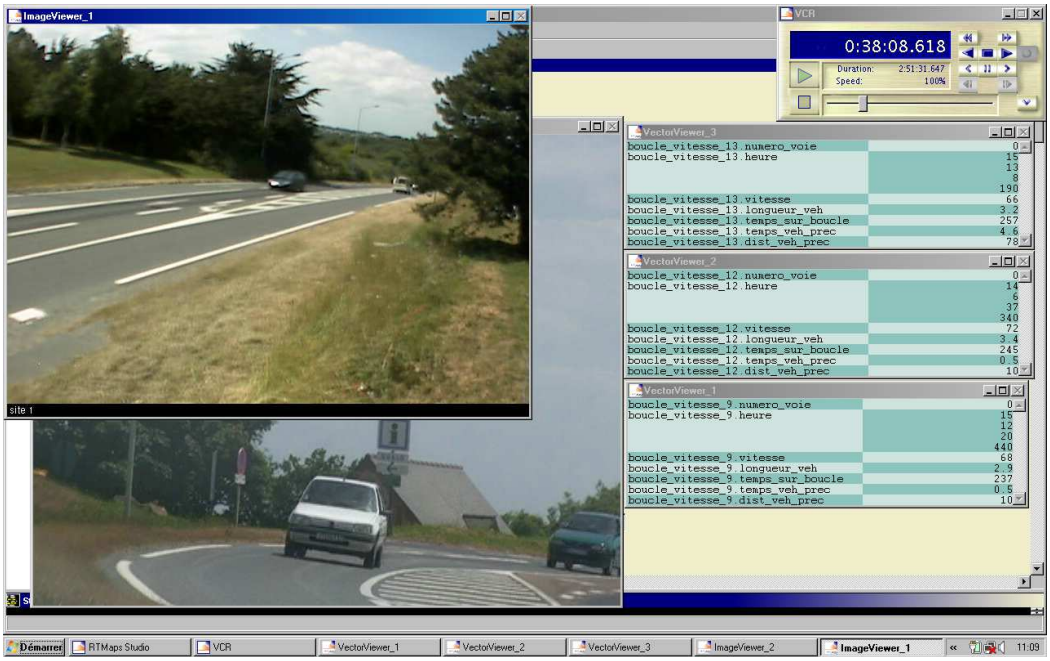

Fig. 54 RTMaps for SARI: synchronization of video records with vehicles data along three geographical points (position in the lane, speed, distance from other vehicles, size of vehicle…).

The SARI project, and in particular the **PhD of Ludovic Duquesne** (Duquesne, 2009), addressed another critical use of data, with the confrontation of data which came from different disciplines highlighting different types of system acceptability: Individual (cognitive), social, economic and legal acceptability. The fact that what is acceptable from one point of view is not obviously acceptable from another means that the decisions are taken according to a multitude of criteria. We initially established one model of each acceptability by direct discussions with experts. All of these models were then synthesized in an inter-acceptability global model which considers all the acceptabilities together. Based on a multi-criterion decision aid methodology, some classification must be made, leading to a reading grid which will help a decision maker to choose an action (Duquesne, Millot, Pacaux-Lemoine, & Crevits, 2009).

4.3.5 Experiments results and their impacts on the Human-Machine Systems

The 12th step of the method (cf. Fig. 32) is the result of all the previous steps. Experimenters may describe the experimental HMS. We will not focus on results here, having already detailed all kinds of results in the section about data records (cf. §4.3.2). This section deals with the impact of results on the descending phase of design. Three main feedbacks aim to update boxes of the design phase.

The first round of feedback (13th step of the method) validates the HMS and updates current models of human operators, assistance systems and processes according to new achievements.

The second round of feedback (14th step of the method) highlights unsuitable aspects in the design of the HMS. Therefore, designers must modify such aspects that may deal with new human tasks, or new assistance tasks, or new Common Work Space, or new organizations. The data processing stage and the proposed tools provide precise information about unsuitable aspects, so designers know precisely where modifications need to be made.

The third round of feedback (15th step of the method) underlines the necessity for participants to have more training with their new tasks, regarding their cooperation with assistance systems, or with the process.

Therefore, the proposed method is an iterative method that experimenters can apply several times until the human-machine system reaches fixed goals. Fig. 55 presents such an iterative procedure based on four main characteristics: the design phase, the evaluation phase, the field of possibilities and the number of iterations. The spiral refinement brings attention to the long design and evaluation phases at the start of HMS design due to the high number of possible systems that could fit the objectives. Nevertheless, the more experimenters iterate the procedure, the more they reduce the number of possible systems and the less phases are long.

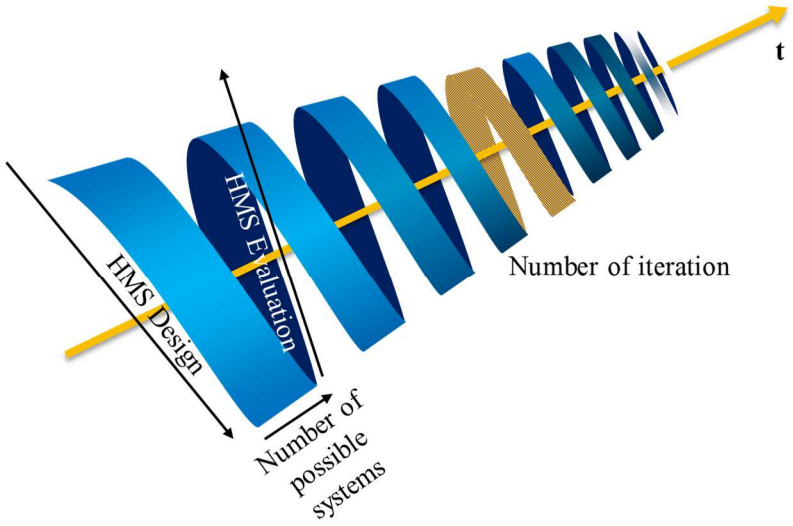

Fig. 55 Iterative procedure with spiral refinement (Marie-Pierre Pacaux-Lemoine & Flemisch, 2015)

4.4 Experimental dimensions

As a conclusion for this part on methodological aspects, we provide a synthesis of all the types of experiments we conducted with a presentation using three dimensions. The first one comprises of the experimental conditions, described according to the realism of the situation, which is the human activity context and type of process. The second dimension deals with the realism of human behavior that evolves from a small samples of humans, who are more or less aware of the process, and the use of new systems, to huge samples equivalent to all end-users. The third dimension is the realism of new system and, above all, its maturity. These three dimensions may help to define the right number of experiments and the right steps from one experiment to the next to be sure of the relevance of these experiments (cf. Fig. 56).

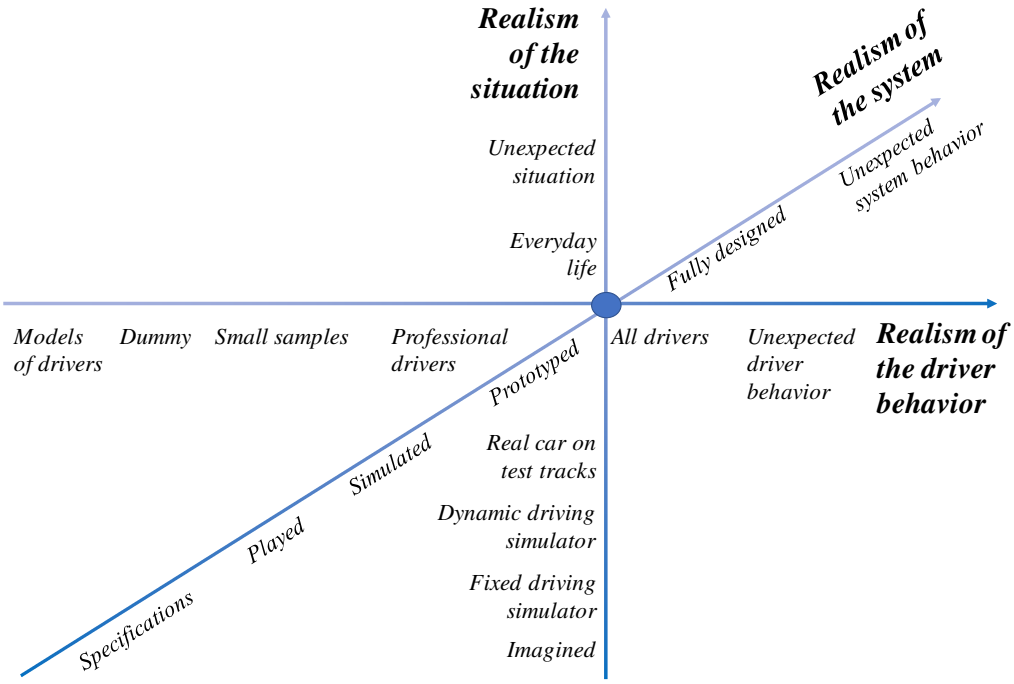

Fig. 56 Three dimensions for experimental design and evaluation in the automotive domain (adapted from (Marie-Pierre Pacaux-Lemoine & Flemisch, 2015))

Each dimension shows examples of states, but more states in between might exist. On Fig. 56, the central point at the intersection of the three axes highlights what we could consider as an end to experiments. However, before achieving this point, several other points describing several types of experiments may exist, and experimenters have to explain and justify how they go from one point to another one in order to be sure of improvements on each axis, as well as the consistency of the successive results.

The next step should be the implementation of new systems as well as the training of human operators. Nevertheless, when implementation of the HMS is complete, the humans involved in the management or in the use of such HMS must make sure that it functions appropriately. Many characteristics of HMS may change and destabilize its proper functioning. Indeed, as made clear by the arrows of the three dimensions, they point toward an "unknown world" in which many unexpected events, good or bad, could occur. Parts of this "unknown world" will hopefully be studied in a new future.

SYNTHESIS ON RESEARCH CONTRIBUTION

My research contribution dealt with the design aspect of HMS, as well as its evaluation (cf. Fig. 57). From the designer's perspective (purple part of the figure), we proposed three main models. The first can be considered as the basis since it defines what is a ***cooperative agent***. The definition uses the concepts of ***Know-How*** and ***Know-How-to-Cooperate*** which were presented at the beginning of my research work. The ***Common Work Space*** also dates from this period and aims to support cooperation between cooperative agents. As for these concepts, we constructed tools to identify what could be cooperation between two agents, and we defined ***levels of cooperation***. This definition is a response to the several taxonomies of levels of automation. Therefore, we proposed a method to identify the ***levels of automation*** designers may need regarding the problematics they have to tackle, and we highlighted the way to make such levels ***adaptable***. Therefore, we extend the model of cooperation between two agents to a model of cooperation between several agents involved at different decisional levels through the definition of the ***layers of cooperation***.

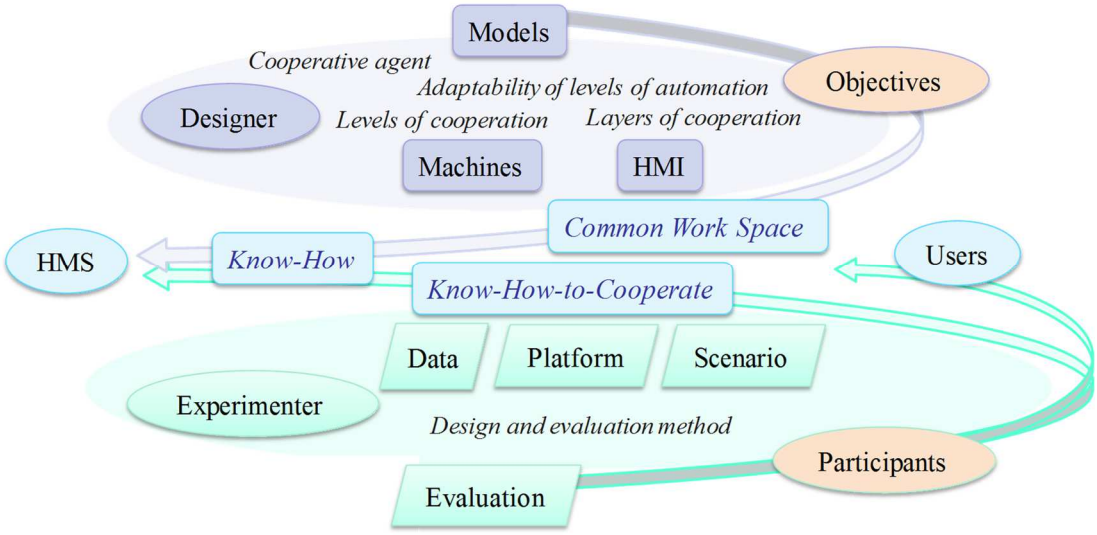

Fig. 57 Research contributions

The other part of my research contribution concerns the evaluation of the HMS provided by the designer. I propose the extension of a method proposed in LAMIH. ***The method*** is based on the previous models for the design and lists several existing or already developed tools for the evaluation phase.

Nevertheless, the HDR is only the state of the research activity at this specific time and even if this work had already been welcomed by the research and industrial community, many other improvements could still be made. The next chapter presents my current intentions regarding such improvements. I am not sure that all the points will be studied, as this will depend on opportunities in terms of projects and collaborations.

Chapter 5. Objectives for the future

"It is probably true quite generally that in the history of human thinking the most fruitful developments frequently take place at those points where two different lines of thought meet. These lines may have their roots in quite different parts of human culture, in different times or different cultural environments or different religious traditions: hence if they actually meet, that is, if they are at least so much related to each other that a real interaction can take place, then one may hope that new and interesting developments may follow". *Heisenberg (1962), Physics and Philosophy*.

"Myth embodies the nearest approach to absolute truth that can be stated in words", *A. K. Coomaraswamy, Hinduism and Buddhism, 1943.*

"(robot) Daneel said, "There is a law that is greater than the First Law. A robot may not injure humanity or, through inaction, allow humanity to come to harm. I think to it now as the Zeroth Law of Robotics." *Robot of the dawn, Isaac Asimov, 1983*

"Robots, perhaps! They lessened the dependence of people upon people. They filled the interstices between. They were the insulation that diminished the natural attraction people had for each other, so that the whole system fell apart into isolates." *Robot and empire, Isaac Asimov, 1985*

The HDR gave me the opportunity to confirm my desire to continue the research activity I had been able to conduct as research engineer, and even increasing it, if possible, with several goals I would like to reach. As it is difficult for me to disconnect my teaching duties from my research work, in the following sections about my objectives, some teaching aspects are also described. Six interwoven objectives will be presented with two sub-parts for each one.

5.1 The generic models

Two main models have been proposed. The first one deals with Cooperative agents' interaction described according to the Know-How and Know-How-Cooperate of each agent, the Common Work Space to support their cooperation (cf. Fig. 23, p. 58) and its use for defining adaptability of levels of automation. The second model deals with levels and layers of cooperation (cf. Fig. 31, p. 69). The models can be improved according to two directions, the analysis of the potential symmetry between Human and machine in order to extract possible functions that can be shared, especially the KHC functions that were not studied enough. Nevertheless, such new shareable functions must be analyzed with great caution, taking in to account ethical aspects. The other improvement concerns the way we use the models in the design phase of the method.

5.1.1 Improvement of the models

The first direction of the improvement is to continue studying the possible symmetry between Human and machine in the system. This was a strong hypothesis when we proposed the model of cooperative agents' interaction and that was fruitful. Indeed, more comparisons could be made in order to check all the aspects in which symmetry might be possible or not. The second direction concerns the answer to the question of symmetry and deals with ethical aspects. Indeed, even if symmetry might be technically possible it might not be ethically acceptable to authorize machine to make risky decisions on behalf of humans and humanity.

5.1.1.1 More symmetry between Human and machine?

With the increase in technological capabilities, system designers can imagine new possibilities for humans to interact with smart systems and delegate some of human functions or tasks to these systems. The interactions and support tools provided by the systems have the potential to be so useful that some authors already argue that they should be considered as symbiotic (Griffith, 2006; Licklider, 1960; Romero, Bernus, Noran, Stahre, & Fast-Berglund, 2016; Tzafestas, 2006). Symbiosis is well known in biology, but if we look at the definition proposed in the Cambridge, Oxford or Larousse dictionaries, we can understand that symbiosis relates to a tight, close, and harmonious relationship that is mutually beneficial yet can lead to vital dependence. From our perspective, this approach implicitly starts to generate some risks. Some have already been identified, like affective (with friends), cognitive (*e.g.* memory, planning support), and psychological (fear of not having access to the machine) dependencies that might emerge as a result of excessive symbiosis (Brangier et al., 2010).

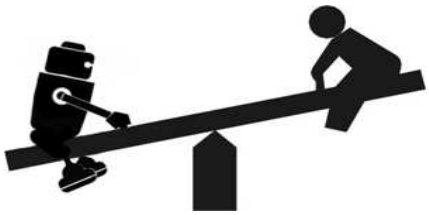

Fig. 58 Where is the equilibrium point for efficient cooperative activity?

Nevertheless, we could adopt a cautious approach to try to improve symmetry between human and machine without falling into risky symbiosis (M.-P. Pacaux-Lemoine & Trentesaux, 2019). We already addressed the notion of trust in the previous chapters, trust hits the human perception of the machine. Quite recently, regarding automation, Balfe et al. identified several characteristics that can contribute to trust (Balfe et al., 2015). The automation must be reliable, competent, visible, observable, understandable, directable, robust, and accountable. Moreover, the automation must provide proactive control and prevent skill degradation. Another kind of topic to approach such characteristics is the notion of transparency.

Transparency:

This concept is not new in Human-Machine System design and analysis. Sheridan and Verplank already explored transparency in the case of study of undersea teleoperation (T. B. Sheridan & Verplank, 1978), Lauwers and Lantz also cited it in regards to shared window systems (Lauwers & Lantz, 1990), while Rasmussen and Pejtersen dealt with transparency of functionality (Rasmussen, Pejtersen, & Schmidt, 1990). The concept of transparency has previously been used in the design of several types of system and may address different parts of the Human-Machine System, *e.g.* the machine reasoning (Van Dongen & Van Maanen, 2013), the interaction with machine (Stubbs, Hinds, & Wettergreen, 2007) and the process (Grote, 2009). Transparency is included in guidelines for the design of complex processes, *e.g.* in Air Traffic Management (Dorneich, McGrath, Dudley, & Morris, 2013), in Air Traffic Control (Göritzlehner et al., 2014; Jans, Borst, Paassen, & Mulder, 2019), in robotics (J. Y. C. Chen & Barnes, 2014; Coppin & Legras, 2012), in manufacturing (Guerin, Rauffet, Chauvin, & Martin, 2019) and in car driving (Debernard, Chauvin, Pokan, & Langlois, 2016). It was recently used to address cooperative activity between several actors within the framework of crisis management (Coletti, Mays, & Widera, 2017; Donovan, Salmon, Horberry, & Lenné, 2018). The importance of transparency has now been demonstrated more and more with the once again increasing capabilities of machines. Correlations have been done with degrees of automation (Chien, Lewis, Sycara, Kumru, & Liu, 2019), with a focus on human-robot interaction (Barnes et al., 2019), and its usefulness regarding the potential impact of Artificial Intelligence and especially machine learning abilities (Fallon & Blaha, 2018).

I would like to address this concept by conducting a deeper analysis of all the references previously mentioned in order to improve the models regarding the transparency of machine. However, particular attention could also be drawn to the transparency of "Human for other Humans", but for machines too. Machines may improve their models of humans if they are more transparent, though ethical questions might be raised.

5.1.1.2 More criteria for function allocation?

The main criteria used in the studies we conducted were agents' competence, workload and awareness. More criteria can be identified and used to manage function or task allocation. Other measurements can also be used to evaluate criteria, like for example mental workload (W. Chen, Sawaragi, & Horiguchi, 2019). Indeed, some types of measurements can be better adapted to the type of user/participant involved in the experiments, and to the type of process and environment studied in a project.

As for other criteria, we already mentioned human transparency, but that must be covered by ethical aspects. Other criteria could be sought and offered to humans, like user preferences (Alexandre, Navarro, Reynaud, & Osiurak, 2019). Another way to try to find the most suitable function allocation would be to adapt the transparency of machine to the awareness needs of the user. As we saw above, not enough transparency may affect Human-machine cooperation due to a lack of information about the other and then a decrease in awareness and trust. However, too much transparency may affect cooperation because the other is too present and disturb the individual activity. In Fig. 27 presented in §3.3 (p.61), we suggested using an extension of the model of Rasmussen to detail three types of cooperative behavior between human and machine; cooperative activities can be skill-, rule- or knowledge-based as for individual activities. Moreover, we consider that these behaviors might be present on each layer of cooperation (M.-P. Pacaux-Lemoine & Flemisch, 2016) and on each level of activity (Abbink et al., 2018). In a study on car driving, Navarro et al. observed the improvement in recovery maneuvers with a motor priming device that is associated to the motor cue with proprioceptive pre-activation of the gesture (Navarro, Mars, Forzy, El-Jaafari, & Hoc, 2010). Motor priming can be considered as a skill-based cooperative behavior. Human supervision of a robot that is moving in a risky environment may be considered as a cooperative behavior based on rules. Indeed, the human knows the cooperative rules and may control the robot's respecting of such rules to be sure that its actions are appropriate regarding the objectives. Examples of cooperative behavior based on knowledge are numerous since this happens each time a human learns how to interact and cooperate with a new machine. Human -machine (UK Ministry of Defence Crown, 2018), -robot (Dias et al., 2008), -agent (Barnes et al., 2019; J. Y. C. Chen & Barnes, 2014; Wohleber, Stowers, & Chen, 2017), -autonomy (J. Y. C. Chen, Barnes, Selkowitz, & Stowers, 2016), -AI (Abbass, 2019), -swarm (Hussein et al., 2018) teaming deal with such an objective: how can we build a team between human and technical agent similarly to all the examples we met between humans in Air Traffic Control, in Military robotics and in two-seater fighter aircraft? The studies referenced above need to be analyzed further in order to extract perhaps more criteria. Nevertheless, I would like to go deeper into the analysis of cooperation between layers of cooperation as we began with Makoto Itoh (Marie-Pierre Pacaux-Lemoine & Itoh, 2015) and with Frank Flemisch (Marie Pierre Pacaux-Lemoine & Flemisch, 2018) in order to improve models and support tools we will design in the future for crisis management, but also with in the new projects on manufacturing management (cf. §7.6.3, p. 162) and in railway traffic management (cf. §7.7, p. 164). Such an objective has recently been proposed in the case of earth-space cooperation with the Multi-Layer Human-Robot Teaming concept (Drepper, Baltzer, Cowley, & Flemisch, 2019).

Ethics:
While Human-machine teaming is an interesting objective, we must nevertheless, as we did for Human-machine symbiosis, take ethical issues into consideration. With Damien Trentesaux, we have recently started to use the model of cooperative agent to identify ethical risks in Human-machine interaction (M.-P. Pacaux-Lemoine & Trentesaux, 2019). Some ethical risks have been identified, such as programmed common sense and bad conscience, decisional ambiguity, mutual interaction, master-slave dependency, emotional dependency, but more work is needed on these aspects. Fortunately, more and more research groups and studies are tackling ethical risks, such as:

- European Group on Ethics in Science and New Technologies (European Group on Ethics in Science and New Technologies, 2018),
- Center of New America Security and Technology and National Security Program on autonomy in weapon systems (Scharre & Horowitz, 2015),
- IEEE regarding ethics of autonomous and intelligent systems (Chatila & Havens, 2019),
- The Royal Academy of Engineering in the UK on Autonomous Systems and the social, legal and ethical Issues (Engineering, 2009),
- and in France, Allistene, which is the alliance of digital sciences and technologies, supports economic and social changes due to digital technology, and in particular with robotics within the framework of CERNA, "Commission de réflexion sur l'Éthique de la Recherche en sciences et technologies du Numérique d'Allistene" (Cerna Collectif, 2014).

Several ethical principles and democratic prerequisites have been written and explained by the European Group on Ethics in Science and New Technologies: "While there is growing awareness of the need to address such questions, AI and robotics are currently advancing more rapidly than the process of finding answers to these thorny ethical, legal and societal questions". The principles and prerequisites address: — Human dignity, — all 'autonomous' technologies regarding delegation of decisions and actions, transparency and predictability, — responsibility, — justice, equity, and solidarity, — democracy, — rule of law and accountability, — security, safety, bodily and mental integrity, — data protection and privacy, — sustainability. Some of these principles haven been mentioned when the models of cooperation were described, but several ones have to be tackled. We have to be aware and integrate the results from all works and issues from these institutes and commissions. That is an important objective for the future if we want to continue with our research on Human(s)-Machine(s) Cooperation, still with a multi-disciplinary approach, even more extended than what we have already done (*e.g.* added value provided by biological, legal, economical aspects). This will be taken into consideration, especially with the design and evaluation methodology, and the way we use the models.

5.1.2 Improvement in the use of the models

One of the results of our studies is that further information about the human working environment is required, in particular with a better and wider consideration of the multi-level and hierarchical aspects of this working environment. We started to go deeper and wider in the analysis of the working environment for which we have to design HMS within the framework of the HUMANISM project (cf. §7.6.2, p.160) and the ongoing **PhD of**

Quentin BERDAL. The main objective of the project is to put forwards a methodology for designing cooperative assistance systems to support Humans in Industry 4.0, especially regarding risks for them in facing complex and uncontrollable systems. The Human-Machine cooperation approach and the way we use our models could be reinforced by the Cognitive Work Analysis approach (Berdal, Pacaux-Lemoine, Trentesaux, & Chauvin, 2019)(cf. Fig. 59).

Cognitive Work Analysis (CWA) was already suggested a long time ago now (Rasmussen et al., 1990) and has been used in several domains of application (Borst, Mulder, & Van Paassen, 2010; Chauvin, Rauffet, Berruet, & Lassalle, 2015; Dadashi, Wilson, Sharples, & Golightly, 2009; Debernard et al., 2016; Horiguchi, Burns, Nakanishi, & Sawaragi, 2004; Morineau & Flach, 2019; Rauffet, Chauvin, Morel, & Berruet, 2015; Neville A Stanton & Bessell, 2014). We are using the CWA approach to define tasks and functions of humans and machines in the case of the control of a flexible cell composed of self-organized systems (smart products) supplied in raw materials and unloaded by mobile robots (Marie-Pierre Pacaux-Lemoine & Trentesaux, 2019). Nevertheless, in the CWA approach, cooperative functions are missing, such as strategies for task allocation, cooperative tasks, detection and management of interferences, as well as cooperation tools. Several points have already been detailed in the HMC approach. Therefore, we would like to analyze how we can combine both approaches to propose a more complete method, especially in domains of application that are vast and complex. A careful reading of previous references may help extract modifications of CWA that have already be made, and help propose added steps.

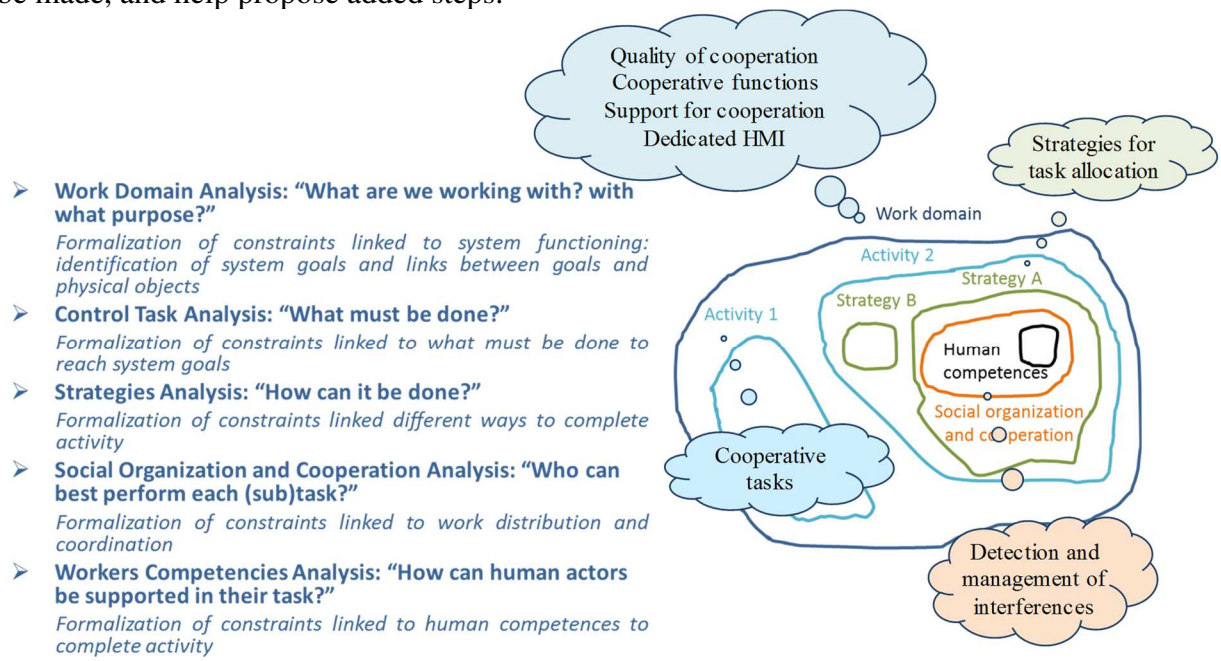

Fig. 59 Use the complementarity of CWA and CMH to propose a stronger method to design HMS, adpated from (Marie-Pierre Pacaux-Lemoine & Trentesaux, 2019).

For example, such a study will be also useful to conduct projects that we have recently started in the railway industry (cf. §7.7, p.164) and will start soon in a clothing factory (cf. §7.6.3, p.162). In both projects, we have to analyze current human activity and existing machines in order to offer and test new jobs and new systems. In the case of manufacturing systems, a lot of work has been carried out regarding formalization and use of competencies, and all levels of activity of the factory are involved. Such work may be useful for having a better overview of the needs (*e.g.* (Boucher, Bonjour, & Grabot, 2007)).

Simulation:

Another interesting way to improve the use of the models is the ability to use the KH and KHC functions, as well as criteria for allocation, as inputs for a simulator to validate their completeness and complementarity from a technical point of view. The flowchart presented in Fig. 24 and Fig. 25 (p.63) can be programmed and executed with several scenarios in order to support the HMS designer. Software environments might support such an objective, with different types of algorithms or methods. Studies in manufacturing systems are used to design such environments in order to support designers to plan human and machine activity taking into account criteria, like for example human fatigue and reliability (*e.g.* (Mouayni, Demesure, Bril-el Haouzi, Charpentier, & Siadat, 2019)), or variability of scenario and uncertainty of data (*e.g.* (Chaabane, Chaari, & Trentesaux, 2009)). FRAM (Functional Resonance Analysis Method) model will be studied again in order to evaluate its suitability for our problematic (*e.g.* (Hirose & Sawaragi, 2020)). However, the implementation of our models in a simulator may also support the online control of task/function allocation during the HMS execution. Methods using petri nets (*e.g.* (Idris, Enea, & Lewis, 2016)) and state machines (*e.g.* (Benloucif, Popieul, & Sentouh, 2016; Rachedi, Berdjag, & Vanderhaegen, 2013)) have already given interesting results. This objective seems to be similar to the one dealing with digital twin and virtual commissioning in manufacturing systems. Digital twin can simulate a process and the agents involved in this process control (*e.g.* (Borangiu, Trentesaux, Leitão, Giret Boggino, & Botti, 2020)). Virtual commissioning aims to evaluate system functionality, performance and safety before its physical assembly and commissioning. In addition, consideration must be given to work dealing with serious games (*e.g.* (Alvarez et al., 2014; Marie-Pierre Pacaux-Lemoine & Mareschi, 2015; Sawaragi, Fujii, Horiguchi, & Nakanishi, 2016)), especially with a comparison with what we have already achieved with micro-worlds and simulated environments. It would be interesting to complement serious game use with the abilities we developed with the Wizard of Oz and theater technics presented in §4.3.3.2. In general, it would be necessary to study the different types of simulation, their advantages/disadvantages regarding the objectives of researches.

5.2 From generic models to implementation

The previous section aimed to improve our models and the methods that may lead to more precise and better adapted models. Nevertheless, one of the interests in having model is to instantiate and implement it to design systems. The following sections propose two main ways that may support the transfer from generic models to functional systems. Both ways are based on research and techniques from two different disciplines, control engineering and computer science.

5.2.1 Choice of control laws

Since our models have identified the KH and KHC that humans and assistance systems are supposed to have in order to cooperate and reach their common goals, the next steps are the implementation of these abilities. Concerning humans, they have to learn and train themselves to achieve the requested tasks and to cooperate with assistance systems. As for assistance systems, they must be programmed by designers. Control engineering can propose many tools to control systems, and most of the time designers use the tools they know or were handled by colleagues involved in the same project, but not the approach that is best suited to the model that is being implemented.

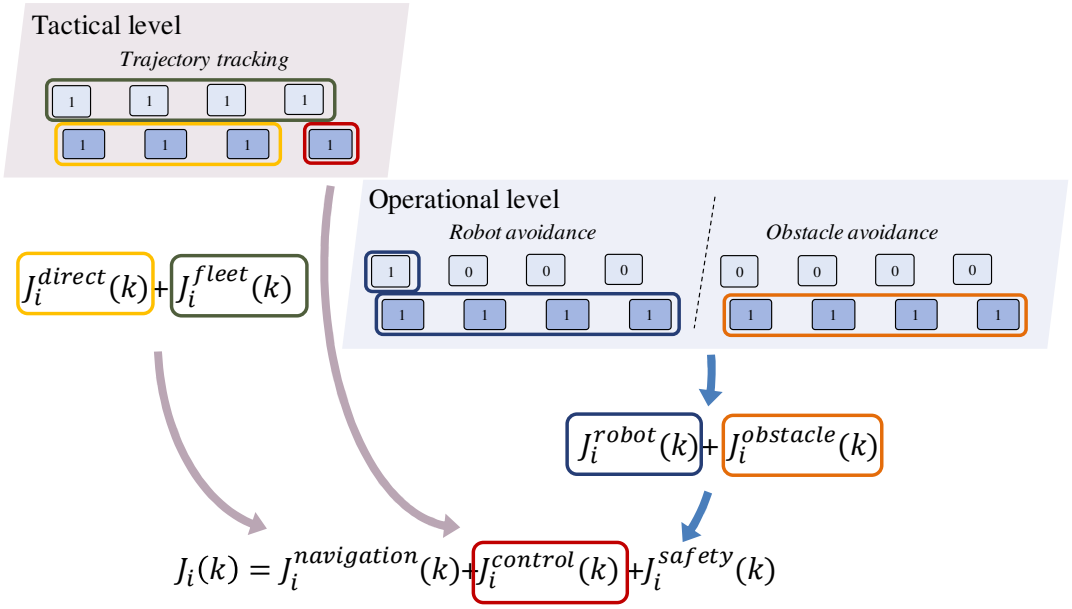

Fig. 60 Know-How (deep blue) and Know-How-to-Cooperate (light bleu) of robot translate to control laws: example with Model Predictive Control

In the project named SUCRé (cf. §7.4.3, p.150), we chose the Model Predictive Control to implement the KH and KHC of robots, but other kinds of implementation might have been better (cf. Fig. 60). We did not have the time to discuss the choice of other techniques with colleagues who were involved in the study, but that is something I would like to explore in the future within the framework of national and international research groups.

The discussions can be conducted to be beneficial for all researchers involved. On one hand, Human-Machine Cooperation approach is oriented to suit control models. On the other hand, problematics from Human-Machine Cooperation approach may question control model possibilities and may lead to their improvement or their extension.

Therefore, control engineering may provide adapted tools to improve the KH and KHC of the machines, but as we already saw in the analysis of the different taxonomies of levels of automation, a mix between control engineering and computer science approaches can be achieved. Both disciplines may provide useful and complementary tools to reach the goals presented previously. These tools are detailed in the next section.

5.2.2 Computer sciences approaches

Computer science objectives, studies and tools may help take advantage of the capacity of Artificial Intelligence systems, Multi-Agents Systems (MAS) and Object-Oriented Programming to complement control engineering models. Such an objective is not new but has rarely been fully implemented. However, thanks to the software environments of both disciplines, which are now beginning to become closer, combination could be implemented and evaluated. This is especially the case when researchers tackle definitions of levels of automation, levels of autonomy and Human-AI cooperation (Abbass, 2019). Different levels of intelligence have also been defined that use foundations from both disciplines (Wang et al., 2019).

They are described as the following:

- reflexive intelligence for sensory-driven intelligence,
- imperative intelligence for trigger-, time-, event-driven intelligence,
- adaptive intelligence for analogy-based, feedback-modulated, regressive-optimized, environment-awareness intelligence,
- autonomous intelligence for perceptive, problem-driver, goal-driver, deductive intelligence,
- cognitive intelligence (knowledge-based, learning-based, inference-driven, inductive intelligence)

Another interesting point is that researchers from MAS are accustomed to organizing functions between several agents, definitely artificial agent most of the time, but the connection and communication are mature. In addition, in control engineering studies, we have an increasing need of these abilities to enable cooperation between several humans and artificial agents from several decisional levels. MAS may help implement such a cooperation.

I had intended to pursue this objective some years ago but did not have the ability to go deeper in that direction (Marie-Pierre Pacaux-Lemoine & Grislin-Le Strugeon, 1998). I hope that the new attempt I initiated in LAMIH with the set-up of the AiAIDo project to respond to the France – Germany –Japan trilateral call dealing with Artificial Intelligence will succeed. We are focusing our attention on the objectives to build a bridge between the human-centered perspectives and the technical and artificial intelligence centered perspectives, with a particular focus on trust, ethics, but also controllability, management of interferences between Human and AI system. We would like to develop and use a new way to anticipate and/or to manage conflicts between human and AI system based on the principles and techniques of the martial art AiKiDo (F. O. Flemisch et al., 2020).

Human-human interference (AiKiDo)	Generic principles	Human-machine systems interference (AiAIDo)
From competition to cooperation, from opponent to partner, all joined to reach common objective	*From Competition to Cooperation*	Human and machine must have and reach same goals, e.g. by embedding explicit or implicit goals into the machines
Escalation- and de-escalation path from harmless to more dangerous back to harmless techniques	*Ai..Do*	Identification of dangerous patterns, development of benevolent and effective human-machine patterns
Tori uses Uke's momentum and strength to get into the center of the attack, tries to control the situation towards a solution	*Controllability from Instability to dynamic stability to harmony (Irimi)*	Arbitration mediator orchestrates a dynamic stabilization of the Human-machine system
Tori manage attacks from several Uke (Randori)	*From one-one to several-several*	Basic principles from One Human/One machine system to multi-human/multi-AI systems
No exclusion, black and white belts work together	*No exclusion Adaptiveness*	Design for all with adaptation and adaptability
Tori/Uke must remain in visual, touch and haptic contact to know other intends	*Keep in contact, transparency*	Human and machine are coupled in a multimodal way and communicate intents
Tori/Uke must not only focus on the other, but develops a mental model of themselves and environment as a common system	*Meta-System-SA (Situation awareness)*	Humans and machines (e.g. AI) build model of themselves, of others and the environment to predict and harmonize actions and results towards common goals
Tori/Uke know techniques and patterns to counter any attack	*Cooperative patterns*	Human and machines have cooperative, compatible patterns to interact
From Uke close to Tori to learn, to Uke farther from Tori to attack faster and stronger	*From simple to complex*	With training human can cooperate with more complex systems.

Fig. 61 Example of the use of a different approach, *e.g.* AiKiDo approach, to analyze and manage Human-AI interferences

Multi-agent systems and object-oriented object programming might help consider both Human and machine as similar agents, from the program's point of view, and with humans represented by a kind of "avatar". Nevertheless, these computer science approaches usually consider humans as a disturbance who are removed from the general system most of the time. Discussions, mutual understanding, common objectives and cooperative work in system implementation and evaluation might address reticence and allow very interesting common studies.

Another field of computer science that can also be connected is that which deals with human-machine interface design. This field is presented in the next section.

5.3 From Common Work Space to Human-machine interface

The models and methods previously mentioned lead us to identify several aspects of Human-machine interaction, and one is the Common Work Space, it supports the external KHC by allowing the collection of information about process and other agents involved in the process control. It supports the implementation of actions as well. In our studies, and as I have already written in this document, we did not focus our research on the ergonomics aspects of the interface available to humans, since we focused on function allocation. Nevertheless, we identified information that must be observable and handled by humans through an interface. Even though we always develop interfaces to implement CWS, cooperation with HMI experts would help improve interaction between human and machine.

5.3.1 Human-machine interface

Several attempts have already been made to use other kinds of interaction instead of the usual visual and sound ones. The project in robotics applied to disabled users, offering them Emulated Haptic Feedback (cf. §7.4.4, p.153). Thanks to a collaboration with the University College of London and the associate professor Tom Carlson, we were able to support cooperation between human and robot by providing an adapted interface, and compensating for the inability of some individuals to control robot except with their brain. Human and robot were able to communicate through the visual interface. It took into account the mental effort of the human to share commands sent to robot (cf. §7.4.4, p.153).

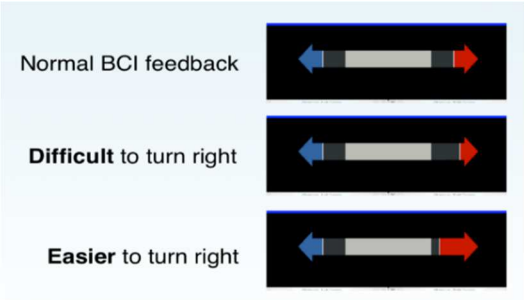

Fig. 62 Emulated Haptic Feedback interface

This project highlighted the great important of the interface, which is sometimes neglect by control engineering designers. I would like to go deeper in the connection between the information we identified with our design method based on our model, and the access to such information and action through interfaces. Various interfaces have been used in each project, sometimes based on existing interfaces like in air traffic control, sometimes completely reimagined like in the human-robots cooperation in the SUCRé project. New displays have been designed, like smart clothes that can support cooperation between robots and firefighters who may not be able to use their hands and watch screens. Haptic feedback is another interface I would like to analyze deeper since it is rich in information, *e.g.* (Devigne et al., 2019). Cooperative patterns could be studied through haptic feedback using a stick in the trilateral France – Germany – Japan project we mentioned, but other kinds of device could be imagined, such as the one put forwards by the Disney research lab. They propose a force jacket which is a "pneumatically-actuated jacket for embodied haptic experiences" (Delazio, Nakagaki, Klatzky, Hudson, & Lehman, 2018). Similar techniques could be used to control natural gesture of Human when sending a command with hand and wrist movement, for example.

These examples deal with the interface between one human and one machine, but several projects underline the increasing need to design interfaces adapted to several humans who have to cooperate, humans who may be assisted by several kinds of machine. This objective is presented in the next section.

5.3.2 Human(s)-machine(s) interface(s)

The need to design interfaces for several humans who have different roles and authorities, but who have to reach a common goal, was especially evident in crisis management projects. In the SUCRé project, the analysis of firefighters' activities highlights such a need. That was due to lack of information shared between the staff who are in the field, in the command post vehicles and in the crisis unit. In this example, there were only three kinds of units among all units that might be deployed in case of crisis. Such an objective has already been mentioned above with the concept of transparency. Nevertheless, in this part I would like to address the technical tools designers can use to implement transparency, namely the kind of interface that can support layers of cooperation.

We started to test the ability to use a tabletop with tangible objects within the framework of a LAMIH project in order to design a cooperative environment for several humans to make strategic or tactical decisions, and to send commands through the modification of position of objects moving on the table (cf. Fig. 63). We proved the technical feasibility. Nevertheless, improvements are necessary. Moreover, experiments must be conducted with well-adapted experiment protocol and several teams of participants. This type of equipment could be very useful in crisis management, especially in the case of firefighters when, in the command post vehicle, several officers may have to make a collective decision. The interest in tangible objects is mainly to make clear, to all those who must be involved in the decision, the intentions of people or machines. Indeed, people handle objects to analyze and decide. The tangible tabletop is one technical technique but other kinds of facilitative tools could be interesting too, like the collaborative transparent displays (Li, Greenberg, & Sharlin, 2017).

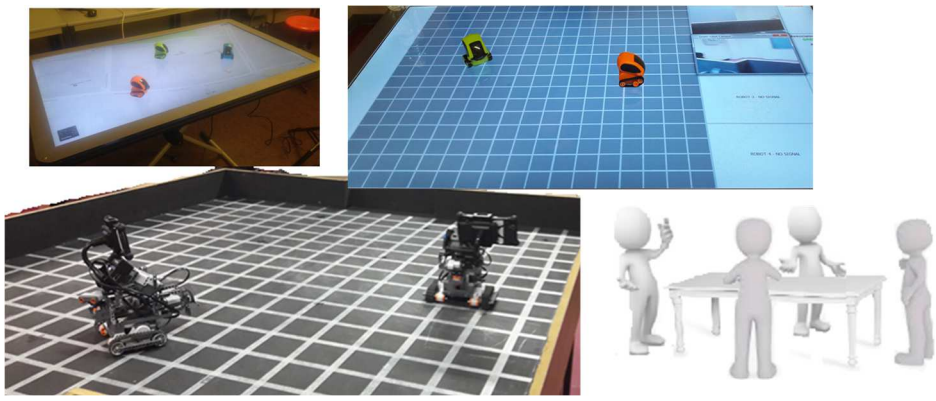

Fig. 63 Tangible tabletop – collective decision making (Merrad, Habib, Héloir, Kolski, & Krüger, 2019; Merrad, Heloir, & Kolski, 2017)

Chapter 6. General conclusion

6.1 Synthesis on the research perspectives

The research objectives presented in this manuscript are synthesized in Fig. 64. As for the research contributions, they still concern the design and the evaluation aspects. It is indeed difficult, for me, to improve one aspect without thinking on how to improve another. With the increasing of abilities and capacities of systems, defined in terms of ***Know-How*** and ***Know-How-to-Cooperate***, new challenges must be considered when designing systems, such as ***ethical risks*** (in purple on Fig. 64). Nevertheless, such risks can be studied partly through improvements we could make with focus on the ***transparency*** of cooperative agents and the ***ergonomics*** of the Human-Machine Interface. Other improvements might also concern tools for designers, such as the use of ***generic models***, the ***simulation*** of the instantiation of these models to check their appropriateness according to objectives, and the way they can be ***implemented*** in the Human-Machine System.

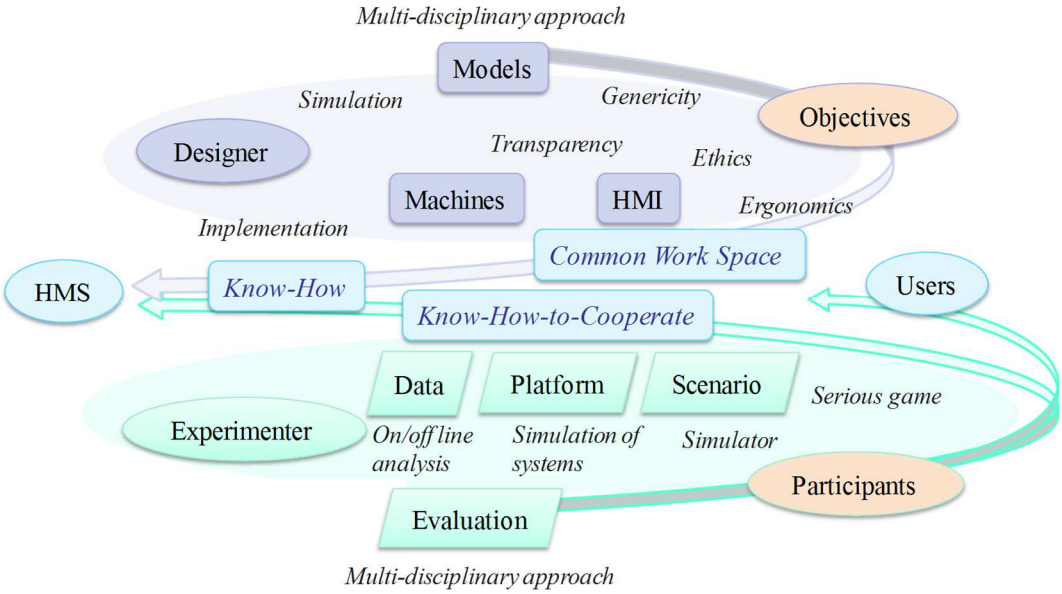

Fig. 64 Synthesis on research perspectives

In connection with the objectives of the HMS design, the evaluation phase (in green on Fig. 64) may take advantage of the generic models to improve the ***on/off line analysis*** of the cooperative agents' activities. In addition, a deep analysis of the possibilities provided by the simulators must be explored, like the ***simulation of assistance systems***, the ***simulation of the technology*** (car, train, aircraft, process) that has to be assisted, or the ***simulation of the environment*** in which the technology is running. Each type of simulation can be improved as well as their interconnections.

The last objective, I would like to present, is the ***multi-disciplinary approach***. We already had some work that brought together several disciplines, but they were casual and dependent on opportunities provided by projects. Deeper work could be conducted in order to go forwards with a more integrative methodology, in which disciplines are not only juxtaposed, but parts of their concepts may be shared, perhaps made collaborative and/or may enrich each other.

6.2 Perspectives on teaching aspects

The teaching aspects have not been described in detail, but they formed part of most of the studies we conducted, especially when some systems were developed and tested with students within the framework of internships or student projects in the lab. One perspective is that this enables us to reach a better balance and organization between lectures, exercises, practical works and projects (cf. Fig. 65). Indeed, since the presentation of research projects during lectures arouses the curiosity of students, an interesting way to maintain curiosity is to explain how exercises and practical work may provide the tools to be able, one day, to join such research projects. Therefore, the continuity between the different types of courses is important and may justify to students the involvement professors are requesting.

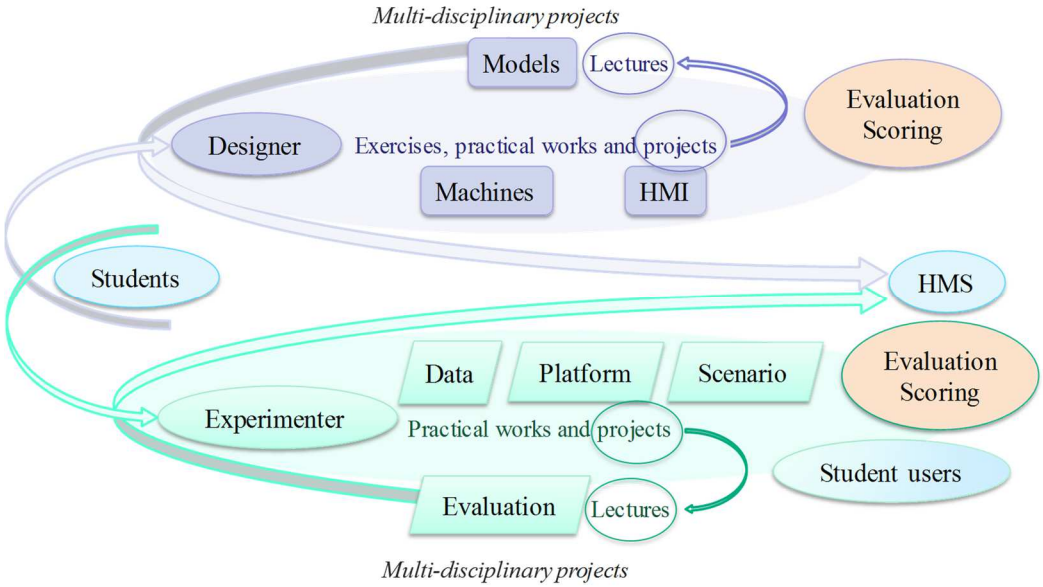

Fig. 65 Perspectives on teaching aspects

As I had started to do last year, I would like to set up courses in which students are sometimes designers, sometimes users and sometimes experimenters. Organizing this is not easy since students, who are members of a same group, know each other and usually do not want to penalize other students. Therefore, the scoring for evaluation is difficult to determine and to implement. Nevertheless, the techniques used during the evaluation phase of the method presented in chapter 4 may contribute to reaching such an objective.

As was the case for the research perspective, this teaching perspective also deals with multi-disciplinary projects. We know that students must be good in the disciplines they are learning, in computer and control engineering and signal processing, *i.e.* the 61st section of the French National Board of Universities. However, in their future jobs they will have to work with people with other competencies. Even though courses about project management are already taught, with a presentation of what other disciplines may bring, it could be beneficial for students to experiment exchange of information, organization of cooperative tasks and achievement of objectives within the framework of lab or industrial project.

6.3 Final conclusion

That is the end of the manuscript, but not the end of my desire to have deeper involvement in the research and teaching activities. On the contrary, this manuscript is not only a synthesis of the contributions gathered for several years (152 documents among which 15 articles in journals and 70 articles in international conferences), in 14 research projects, with 10 PhD students, with numerous and fruitful contacts with French and foreign researchers, French technicians and engineers from labs and industries. It is, in fact, several syntheses correlated, through the manuscript, to provide complementary tools for the design of Humans-Machines Systems (2nd and 3rd chapters) and their evaluation (4th chapter). These three chapters push the synthesis forward a stronger and stable state of my thoughts.

The manuscript also highlights connections between teaching and research, respectively linked to the use and the improvement of computer and control engineering tools. Moreover, these reframed bases underline the research directions I would like to explore, some of which I have already begun to do so. Nevertheless, with the "Habilitation à Diriger des Recherches", I would be able to adapt "the level of autonomy" I am able to accord myself, from no responsibility to full autonomy and responsibility, depending on the topics research projects and calls may offer, and in agreement with the heads of the institutes with whom I will work.

To conclude, I would like to reiterate one of the objectives presented in the introduction. The outcome of the research activity, as well as the concepts, methods and abilities provided to students have to converge towards real advances for humans, for humanity and for its environment.

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Chapter 7. Appendix 1: Projects, implementation to various application areas

7.1 Air Traffic Control

Academic and socio-economic partners: CENA (the French acronym for Center for Air Navigation Studies), DGAC (the French acronym for General Direction of Civil Aviation), En-route air traffic control centers of Reims and Athis-Mons (Paris), Eurocontrol.

Projects: SPECTRA V2, SWIFT (1992-1998)

Role: I was a PhD student

Scientific outcomes:

- **3 articles in international journals: [10][11][12]**
- **11 articles in proceedings of international conference with selection committee: [82][85][86][87][88][89][90][91][92][93][94]**
- **Several reports among which [151][152]**

Scientific Context: The objective of the project conducted in air traffic control was to control the workload of the "radar" air traffic controller, the controller who communicates with pilots to provide acknowledges and orders to avoid air-misses between planes. Literature and past projects in this field highlighted the possibility of assisting controllers with a system able to detect potential air-misses and to provide solutions for the simplest air-misses between two planes. Therefore, the assistance system, called SAINTEX, controlled a portion of the air-misses according to two types of authority management, *i.e.* human or machine decides allocation. The results reflect the outcome of the usefulness of SAINTEX, but suggested another way to control task allocation that was an additional task for the radar controller. Air control organization was the base to propose new assistance system and new studies. Radar controllers works with planning controllers who coordinate the traffic in their own sector with the traffic in other sectors in order to avoid insoluble conflicts at the sector's borders. They were well aware of their teammate workload. Nevertheless, an assistance system able to detect radar controller overload, called PLAFF, offered possible task allocations for SAINTEX to planning controllers. Therefore, the multilevel aspects of cooperation with planning and tactical levels were identified as a solution for improved safety and performance of the general humans-machines system, but as well as for improved human confidence and consequently acceptance of the automatic control.

Fig. 66 Air traffic control platform

Research activities within this context: I was involved in the design and implementation of both assistance systems on the experimental platform that was also designed in the lab. I participated in the setting up and management of experiments, as well as contributing to data analysis, a conference and journal papers and writing reports.

We conducted several studies in the field and spent several days with air traffic controllers, in Athis-Mons and Reims, in order to be sufficiently immersed to feel and understand controllers' needs and requests regarding the increase of air traffic. We were able to perceive individual and cooperative activities in the control room. Therefore, we identified, proposed and evaluated the new notions of Know-How and Know-How-to-Cooperate, as well as Multi-Level Cooperation, especially through the analysis of experimental data supported by MacShapa software. This software supports the analysis of several types of data, and especially the coding of verbal reports recorded during experiments and during debriefings.

We conducted experiments in the control centers on the platform designed by LAMIH, and also on the platform designed within the framework of the European project SWIFT (Specification for controller working positions in future air traffic control). European experiments evaluated new interfaces, like the electronic strip board (a strip describes the flight plan of each aircraft entering the controlled sector), as well as new assistance systems, like the conflicts detection, now implemented on the air traffic controllers' workstation.

7.2 Car driving

More and more studies deal with car driving and the objective of finding solutions to tackle the increase of traffic as well as the increase of drivers' needs. The increase in traffic entails an increase in the complexity of the driving environment. The increase in drivers' needs includes the drivers' comfort, but also the need to be autonomous, *e.g.* to move despite some disabilities due to accident or age. Automation can be a possible answer to such needs. Systems designed for the car-driving domain today are able to fully control the car in specific driving situations. They also gather information from the environment and diagnose problems regarding driving conditions and other road users. They have even started to diagnose driver behavior regarding driving situations and the driver state. Advanced Driving Assistance Systems (ADAS) can partially or even fully take over from humans. However, what is the risk of implementing such a system? Systems can improve the way automobiles are used today, but what will the impact be on drivers' behavior, on their interaction with the ADAS and the other road users involved in the traffic that are progressively equipped?

The objective of this section is to present several studies conducted in order to provide some preliminary responses to the previous highlighted needs and questions. This section presents some ADAS and on-road systems, as well as results stemming from experiments conducted in the field and on driving simulators. Before such descriptions, an overview of risk taking in automobiles by drivers, but also by system designers, presents a model gathering different types of interactions between driver and several other entities involved in the driving environment. This model is useful to highlight the objectives of the projects presented in the following sections.

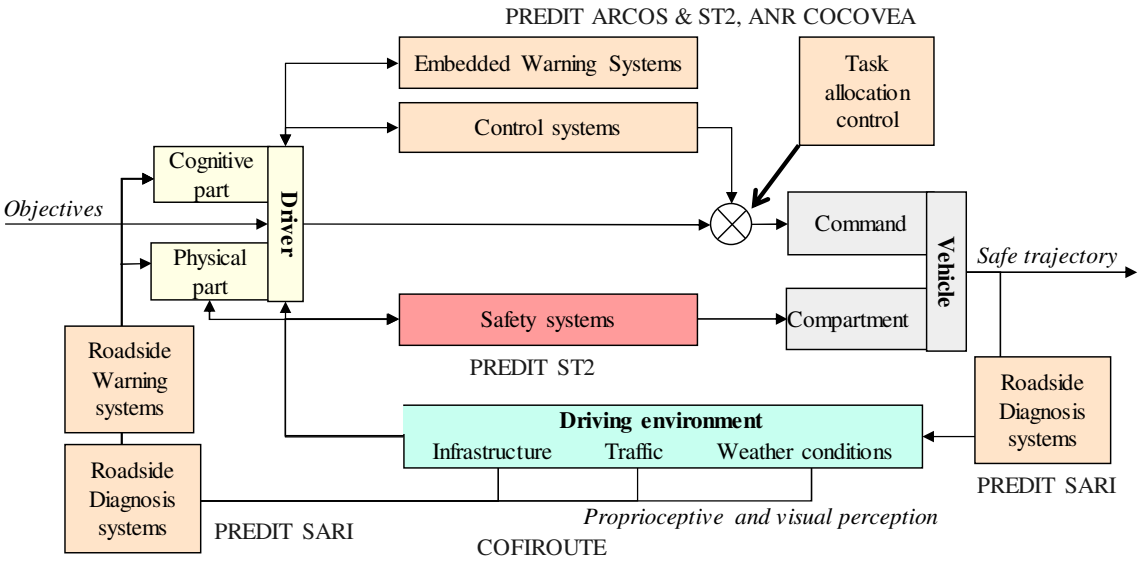

Fig. 67 Driving environment and driving assistance systems

The driving environment is a dynamic process based on the combination of infrastructure, weather conditions and road users. Drivers are part of this dynamic process by controlling their cars in order to reach their destination safely (cf. Fig. 67). The model highlights the distinction between the command part and the physical part of the driver, as well as between the vehicle and systems. Both parts are of course strongly interconnected, but such distinction underlines the distinctions also made for systems design. In fact, systems

are most of the time designed independently of each other. Nevertheless, with the increase in systems' abilities and complexity, more and more projects focus on systems' compatibility and coherence. The cognitive part is the problem-solving ability that allows the driver to analyze the driving situation and make the right decision at the right time. Embedded or on-road driving assistance systems may support this part by warning against risky driving situation or by controlling the car for driver comfort and safety (command part of the vehicle). The physical part includes the ability of the driver to gather information from the environment, from the vehicle and the systems, and the ability to act in the vehicle in order to implement decisions. However, the physical part is also the part that safety systems and compartment must protect when an accident occurs by taking into account the driver's position in order to adjust protections dynamically.

7.2.1 Car driving - Embedded Driving Assistance Systems

Academic and socio-economic partners: PSA, Renault, OKTAL, University of Tsukuba (Japan)

Projects: PREDIT ARCOS (2002-2005), ST2 (2004-2008), ANR COCOVEA (2013-2016), International collaboration

Scientific outcomes:

- **14 articles in proceedings of international conference with selection committee: [38][46][52][64][70][71][72][74][75][76][77][78][79][80]**
- **8 reports: [123][134][135][136][137][138][140][142]**
- **3 seminars: [108][109][117]**

Scientific Context: The objective of these three projects was to design and evaluate advanced driving assistance systems (ADAS) on the Université Hauts-de-France's driving simulator. Warning systems about traffic situations and cruise control systems (cf. Fig. 68) were simulated with the Wizard of Oz method (ST2) and/or implemented (ARCOS, COCOVEA) to be evaluated with participants. Main results dealt with the awareness of drivers regarding ADAS mode, mode changes as well as ADAS abilities according to driving situations. We improved and adapted the analysis method designed in the air traffic control domain, supporting the coding of human and system activities during experiments based on log files and verbal reports.

Research activities within this context: I was involved in the design of ADAS, in the design and implementation of the Wizard of Oz method to control ADAS, but also traffic, from the experimental room that allows the control of the driving simulator and experiments (scenarios, assistance systems). I participated in the settings up and management of experiments, as well as contributing to the data analysis, conference papers, a book chapter and writing reports.

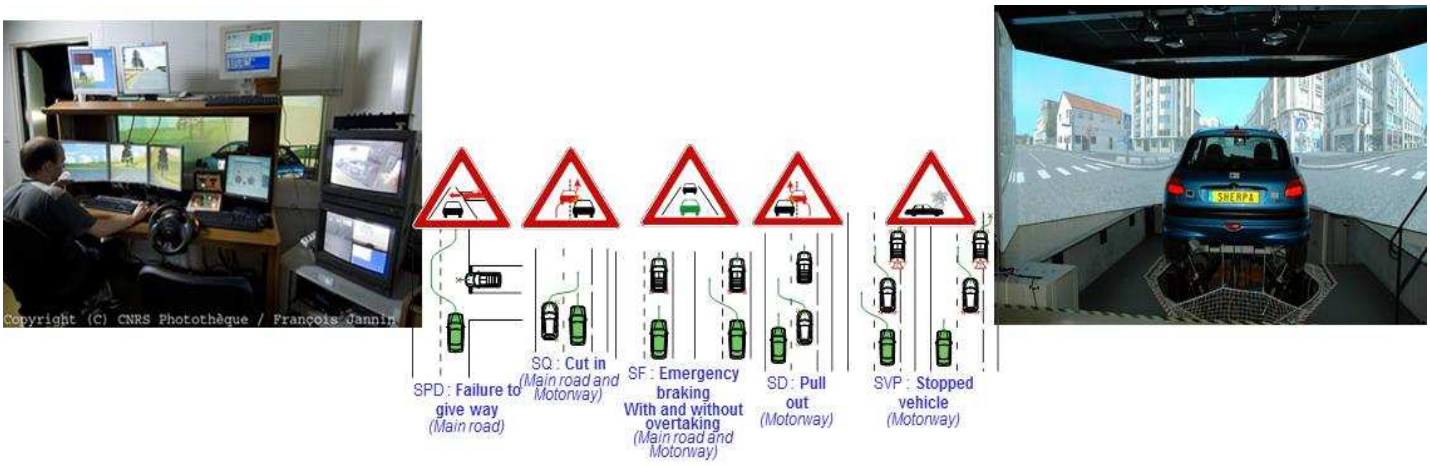

Fig. 68 Control room – Risky driving situations – Driving simulator of the Université Hauts-de-France

7.2.2 Car driving - On-road driving assistance system

Academic and socio-economic partners: LCPC & INRETS (now IFSTTAR), LRPC Saint-Brieuc, CETE-NC, Erdyn consultants, GMConseil, LAUREPS (Université Rennes), LAA (Université René Descartes)**,** ESEO (Ecole d'ingénieur Angers).

Project: PREDIT SARI (2005-2010)

Role: Leader of AJISE sub-project for LAMIH.

Scientific outcomes:

- **3 articles in international journals: [4][5][8]**
- **5 articles in proceedings of international conference with selection committee: [47][58][59][60][61]**
- **2 articles in proceedings of national conference with selection committee: [95][96]**
- **7 reports: [124][125][126][127][129][132][133]**
- **1 seminar: [113]**

Scientific Context: The objective of the SARI (Automatic Road Condition Monitoring to provide Information to Drivers and Road Managers) project was to study new technological solutions to road safety, especially on rural roads with the limited budget of local communities and the inability to improve road security by rebuilding roads. In 2004, the severity (deaths/100 injuries) was also 3.9 times higher on rural roads than in urban areas. The project proposed and evaluated new solutions according to four main sub-projects (cf. Fig. 69):

- RADARR (Research into Attributes for Early Diagnosis of Road Discontinuity) dealt with risks due to dangerous bends combined to the position of the vehicle in the lane;
- IRCAD (Informing road users about the risk of discontinuities in the route due to poor weather) dealt with risks due to slippery roads combined to vehicle speed;
- VIZIR (Intelligent vision of risky roads and zones) dealt with risks due to loss of visibility because of road layout or masking (vegetation, buildings).
- AJISE (Acceptability in legal terms, to individuals and society and from the economic standpoint) dealt with the ability to analyze previous risks according to different points of view.

Research activities within this context: I was involved in the AJISE sub-project to coordinate technical solutions proposed by the other sub-projects and to conduct experiments on driver simulators and in the field on several risky roads identified in Côte d'Armor and in Maine-et-Loire French departments.

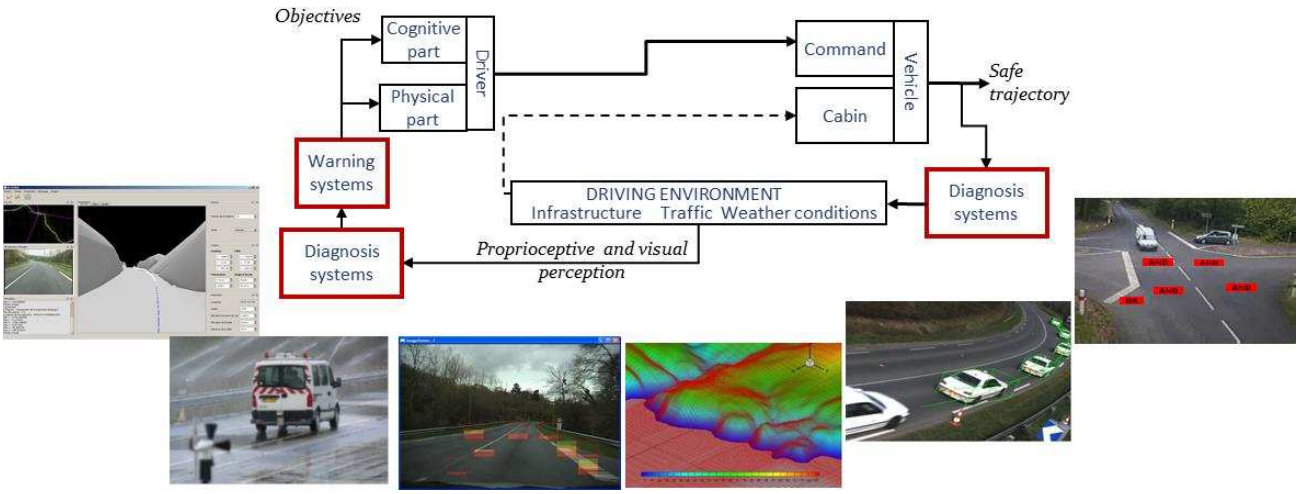

Fig. 69 Technical solutions implemented and evaluated in PREDIT-SARI project

I was especially involved in the study focused on the risk related to crest vertical curves (CVC) on rural roads, using a field site managed by a local operator of the French road network (Conseil Général de Maine-et-Loire, 49). The final goal was to test one road treatment on the real road. The first step, using driving simulators, determined the two most effective perceptual treatments (i.e., rumble strips on both sides of the centerline and sealed shoulders) in order to help drivers to maintain lateral control when driving on CVCs. In the second step, where we were evaluating the impact of perceptual treatment on the field site, a diagnostic device was developed and installed, in order to track the individual paths of vehicles around the target CVC in the field site. By observing these paths, the third step involved collecting the data during two periods. The first before setting up the centerline rumble strips (CRS), and the second after the setting them up. This way, we evaluated the impact of the CRS on the driver's behavior, and we compared the results obtained in the field study with those of the driving simulators' studies. This comparison showed that the trends observed, both in driving simulators and on the real site, were similar.

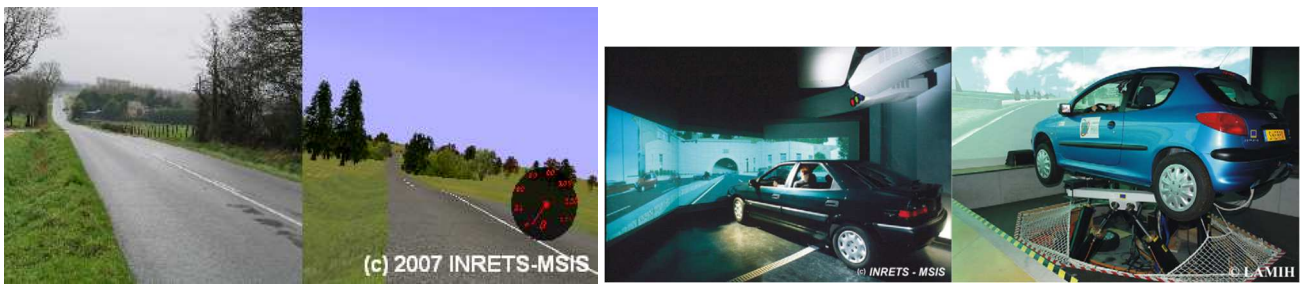

Fig. 70 Evaluation of the impact of perceptual treatment in the field and on two driving simulators: fixed-based one on the left and motion-based one on the right

Acknowledgments

The research was performed as part of the French national project PREDIT-SARI (sub-themes VIZIR and AJISE) sponsored by the Department of the Environment, Energy, Sustainable Development and Sea (MEEDDM). We would like to thank Isabelle Aillerie (INRETS-MSIS) for constructing the 3D databases and for her help with replicating the experiment with the fixed- and the motion-based driving simulators. And I would like to thank Jean-Michel Auberlet from of Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR) for our rich and fruitful discussions and works.

7.2.3 Car driving - Driver behavior during pre-crash situation

Academic and socio-economic partners: LAMIH: "Human and Life Sciences", "Automation and Control" and "Mechanical Engineering" departments, LAB (Laboratoire d'Accidentologie de Biomécanique et d'étude du comportement Humain), and University of Tsukuba (Japan) within the framework of the visiting professor application with Makoto Itoh (2011-2012)

Project: ST2 (French acronym for Science and Technology for Transport Safety) (2004-2008)

Scientific outcomes:

- **3 articles in international journals: [6][7][9]**
- **2 articles in national journal:[13][15]**
- **8 articles in proceedings of international conference with selection committee: [53][55][56][65][66][67][68][69]**
- **2 articles in proceedings of national conference with selection committee: [97][98]**
- **1 seminar: [114]**

Scientific Context: The objective of the project dealt with drivers' emergency-avoiding behavior while they are driving a car in a rural area. A significant improvement in active and passive safety technologies for vehicles has helped to reduce the number of accidents and the damage due to an accident significantly. Active safety systems work before a crash occurs and nowadays have preventive functions to avoid a crash. Passive safety concerns the period after the crash in order to protect occupants or to reduce the occupant injuries. In order to quantify the efficiency of the passive safety systems, European normalized crash tests are performed with crash test dummies. Therefore, the tests of the passive systems efficiency do not take into account a large panel of driver anthropometries, the real comfort driving position and the real driver reactions facing a crash. Our objective was to test the ability to evaluate drivers' behavior during a virtual crash situation on a driving simulator, to analyze risks of drivers Out Of Position (OOP) regarding the way and the time airbags are triggered and to propose different ways to protect the occupants. The potential solution studied was the possibility of detecting crashes earlier and to have better control over airbag inflation. Based on behavioral data obtained from experiments conducted with the driving simulator of Université Polytechnique Hauts-de-France, we analyzed the driver's behavior just before the collision. The results showed that it would be possible to characterize OOP of drivers. Madymo® digitally reproduced such positions with the ellipsoid Hybrid III dummy model and performed a numerical simulation of a frontal collision at 56 km/h. The results of the computational runs put forward injurious situations when the driver's arm was in front of the steering wheel. Indeed, in this case, the arm could hit the head under airbag deployment and cause the neck to be bent seriously and the head to be thrown violently back.

Another result highlighted the tendency of drivers to choose a "rational" behavior to avoid the collision by using the available visual cues even though the situation is extremely time critical. Indeed, the result was interesting in a sense that people can choose an "appropriate" alternative in time even under severely critical conditions. However, the choice of the alternative is based only on available information and not on hidden hazards. If the hidden hazards are taken into account, the alternative chosen by the human may be inappropriate. This finding may be useful to design protective ADAS that work in crash situation.

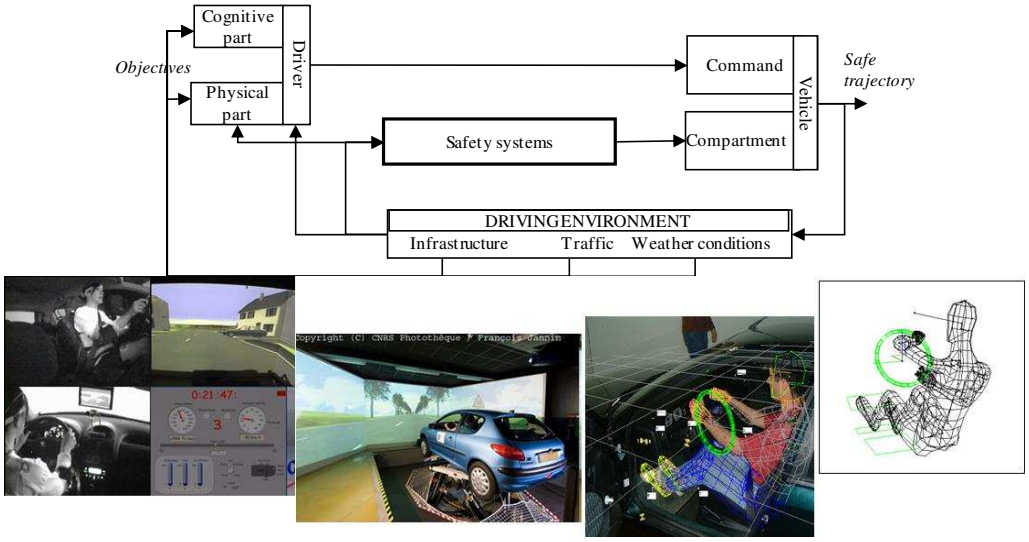

Fig. 71 Control of experiment and data recording; Scenario; digital car and OOP

Research activities within this context: I was involved in the ST2 project to manage two experiments conducted, first on the fixed-based driving simulator that became the motion-based one used by Université Polytechnique Hauts-de-France today. About one hundred drivers experienced a virtual crash situation during the first or the second experiment (cf. Fig. 72). We were able to analyze the behavior of 76 of them. The main difficulty was the synchronization between all types of data. Log files and video records supported the extraction the force applied on the brake pedal, the moment applied on the steering wheel, the speed of the steering wheel, the car speed, the distant from line crossing and the time for drivers to move from the accelerator pedal to the brake pedal. Thanks to the use of the so-called BCD (Benefit/Cost/Deficit) model, we found that emergency (deficit) in the crash situation could be detected with an average time of 0.98 s.

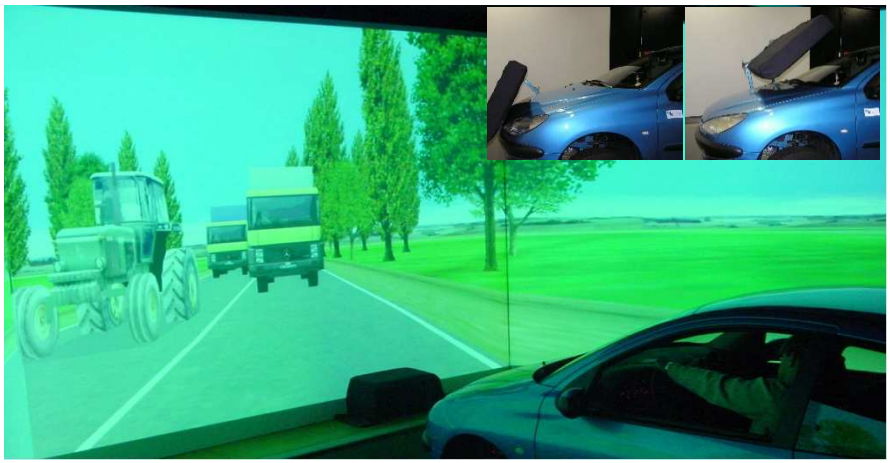

Fig. 72 Scenario of the unavoidable crash situation; Sequence of the falling block on the windscreen

Acknowledgments

This research work was supported by International Campus on Safety and Intermodality in Transportation the Nord-Pas-de-Calais Region, the European Community, the Regional Delegation for Research and Technology, the Ministry of Higher Education and Research, and the National Center for Scientific Research. We gratefully acknowledge the support of these institutions.

7.2.4 Car driving - Infrastructure impact

Academic and socio-economic partners: Cofiroute (the French acronym for Industrial and Financial Company of Motorways), Oktal, Renault (French car manufacturer)

Project: Project commissioned by the French Transports minister to Cofiroute (2002-2003)

Role: Leader of the experimentations conducted on the driving simulator.

Scientific outcomes:

- **1 article in proceedings of international conference with selection committee: [73]**
- **2 reports: [139][141]**

Scientific Context: The French government selected Cofiroute as the main contractor for building, operating and maintaining the A86 west tunnels. This future tunnel will house two superposed, independent carriageways, each carrying one-way traffic. Each level is divided into a two-lane carriageway. The tunnel is 10 kilometers long and between 20 and 90 meters deep. The ceiling height is 2.55 meters and the speed is limited to 70 km/h. Literature dealt with the most stressful aspect of this type of environment, its brightness. Moreover, the tunnel only provided a hard shoulder for emergency use and refuge areas on the left side, when the usual positioning in right-hand drive countries is the right side. Therefore, the study had to analyze drivers' perception and behavior during normal and risky driving situations, as well as the impact of the positioning of the hard shoulder on the left side of the road on traffic patterns.

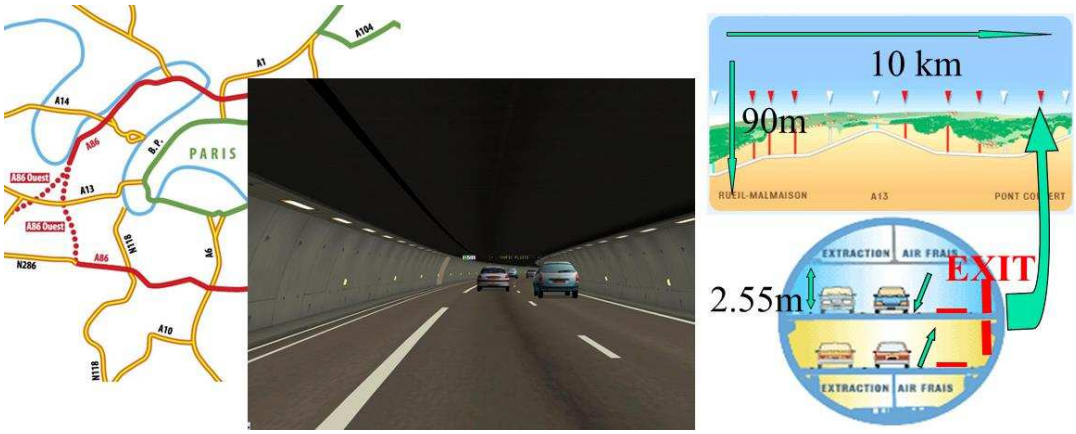

Fig. 73 Tunnel virtual mock-up; Tunnel characteristics

Research activities within this context: I was involved in the definition of the experimental protocol built with nine traffic situations. We conducted experiments with 38 participants. We recorded data about the interactions between drivers, the vehicle and the environment, as well as driver posture, spontaneous verbalizations and the drivers' comments during the replay. The experiments took place on a motion-based driving simulator installed at Renault's Technocentre. It is a full-scale instrumented Renault Clio cockpit (cf. Fig. 74).

Fig. 74 Driving simulator in the Technocentre of Renault

The results showed that in normal driving conditions, with no risky traffic situations and without offences, drivers have in mind the position of the hard shoulder and, even if it is on the left side of the road, they never use it. This behavior is perhaps due to the particular conditions of a simulation, where drivers felt someone was watching their behavior and so respected the hard shoulder rules. However, during two risky situations, when the driver or another vehicle had to go on the hard shoulder because the vehicle is breaking down, problems appeared. Drivers exhibited behavior based on reflex and stopped the vehicle on the right-hand lane instead of going on the hard shoulder on the left. Some drivers made the mistake of overtaking vehicles using the hard shoulder. Some drivers also thought that it was too dangerous to cross the left lane to go to the hard shoulder, because in France the left-hand lane is the faster one. Drivers' comments made it clear that they need better signs and markings for the hard shoulder, perhaps with zebra markings and/or sound rough markings. They would have confidence in the tunnel's surveillance cameras and hoped that traffic infraction would be punished. Several drivers specified that they preferred to drive in the central lane of the tunnel, i.e. in the left-hand lane if the hard shoulder is on the left and on the right-hand lane if the hard shoulder is on the right. They said that the slowest lane should be close to the hard shoulder, because if they have a problem, they should be able to join it quickly.

Acknowledgments

We wish to thank Oktal and Renault for their contribution to this study.

7.3 Fighter aircraft

Academic and socio-economic partners: CNRS (the French acronym for Scientific Research National Center), Dassault-Aviation, DGA (the French acronym for French defense)

Project: Human-Human cooperation and its assistance in the field of fighter aircraft piloting (1998-2001)

Role: Leader on the engineering control component and responsible for the design of the experimental platform in LAMIH.

Scientific outcomes:

- **3 articles in proceedings of international conference with selection committee: [63][81][83]**
- **8 reports: [143][144][145][146][147][148][149][150]**

Scientific Context: A scientific collaboration between Dassault-Aviation, CNRS and DGA dealt with human-human cooperation and its assistance in the field of fighter aircraft piloting. The research program had many goals. The first one was to study cognitive cooperation in the cockpit of a two-seater fighter aircraft, between the pilot and the weapon system officer (WSO). A preliminary study leads to studying their real tasks and to observing their activity in a simulated situation. The second goal offered some possible directions for designing assistance systems to support pilot and WSO cooperation in degraded and unexpected conditions (deteriorated situations or new missions). Moreover, their means of cooperation might be helpful to design assistance systems to support cooperation between the pilot and other actors of the battlefield (*e.g.* controllers of AWACS (Airborne Warning And Control System)), as well as cooperation between remote human operators and UCAV (Unmanned Combat Air Vehicle). The main goal of this study was to determine the impact of different levels of development of the Common Work Space (CWS) on the cooperative activities in the cockpit. The CWS consisted in enriching the representation of team activity according to temporal and spatial formats, which was mainly based on the usual tactical situation representation (SITAC). With the CWS, humans could access to information provided by other humans, and supply their understanding of the situation by providing their information gathering, diagnosis, decision-making and actions in a more or less automatic manner. Results showed that the integration of such a rich representation of the battlefield improved cooperative activity. More recent fighter aircrafts are now equipped with such an interface.

Fig. 75 Fighter aircraft experimental platform and Common Work Space (more details on Fig. 48)

Research activities within this context: I was involved in the design of the experimental platform, a generic two-seater fighter aircraft simulator, which was an adaptation of Dassault-aviation aircraft simulators. With this platform, we were able to implement and control new IHMs, and to control scenarios during experiment, thanks to the Wizard of Oz method. We conducted experiments with pilots and WSO of Air Force Bases of Luxeuil (12 crews) and Cambrai (4 crews) in France. Both pilots and Weapon System Officers were able to perform every task (dynamic task allocation is possible, as it is in actual work, but to a larger extent). Missions are divided, most of the time, into three or four main stages: (i) going near the target (entering the enemy territory and flying to the target, steering clear of enemy threats), (ii) handling one or two targets (reconnaissance or destruction mission), and then (iii) leaving the enemy territory.

The crew mainly made up the content of the CWS during mission planning. They added all the information they wanted along a spatial representation of the flight plan, *e.g.* mission orders, targets, the flight plan, flight rules, and individual and cooperative tasks of each one like ATC or AB3C radio contacts, activation or deactivation of functions and function options, altitude and speed control and the preparation of weapons.

The analysis of the answers to the questionnaires, cooperative activity during mission completion and use of assistance systems, were possible thanks to the automatic and manual coding of all crews' activities. Results showed that the crews used the CWS as short-term and long-term assistance tools. They handled this interface during low workload periods, whereas during high workload periods they did not have sufficient resources available to do so. Nevertheless, the automated update of common information may help. Our results also made lack of training clear. The crews did not have enough time to learn how to make use of the assistance tools and to embed their usual work procedures in them. However, we showed that this type of cooperative support prevented the crews from interrupting each other's tasks, especially when they were fully involved in their own task. Another important result was that CWS facilitated crews' cooperation even if the mission forbad radio communication for security and safety reasons.

Acknowledgments

This study was done in collaboration with Dassault-Aviation. I would like to thank the Dassault-Aviation Istres test base staff Dassault-Aviation Saint-Cloud staff for their collaboration. The experimental field was the Air Force, especially Air Base 116 and 107. I must thank 2/4, 1/4 and 1/12 Air Force squadrons for their warm welcome and their cooperation. I would also like to thank the IMASSA-CERMA staff for their help, J.-M. Hoc and R. Amalberti for their precious advice during this study.

7.4 Robotics

The origin of the word “robot” is a Slavic stem (robota) dealing with chore or serfdom. The theatre play by Karel Čapek, “Rossum's Universal Robots”, used “robot” for the first time in 1920. With the technological improvements of sensors, processors and other mechanical and electronic components, robots are considered more and more as a machine that can be very close to human activity for several aspects, like a human companion. Indeed, robot can perform all functions of the cooperative agent model (cf. chapter 0), with tactical as well as with operational objectives. Therefore, this domain of application is very useful to evaluate our models and methods, and four projects support such studies. We conducted three studies with safety objectives (§7.4.1 to §7.4.3) and one study to support disable people (§7.4.4).

7.4.1 Ground robotics in a simulated military context – MIX

Academic and socio-economic partners: Master’s students

Project: Master’s students’ project (2013-2014)

Role: Supervisor of Sarah Hammiche and Maxime Sédilot (Master’s students)

Scientific outcomes:

- **1 article in proceedings of international conference with selection committee: [39]**

Scientific Context: The objective of this study was the evaluation the impact of Unmanned Ground Vehicle (UGV) autonomy, combined with task complexity, on human performance and situation awareness. The virtual environment software MIX (Mixed Initiative eXperimental), dedicated to studying warfighters’ needs in the domain of robotic military equipment and unmanned systems, supported such evaluations (Barber et al., 2008; Cosenzo et al., 2010a). Humans and machines performed three types of task in order to reach a common goal. The operational tasks were to move into a city and to detect threats. The strategic task consisted in designing the UGV trajectory given a geographic goal and detecting threats. Operators had pictures of targets they had to find in the environment. Two LoAs defined the way operators could interact with the UGV. On the first level, operators remotely controlled UGVs using a joystick (teleoperation). On the second level, operators preplanned UGVs’ routes defined by series of waypoints. MIX includes an Operator Control Unit (OCU) (cf. Fig. 76).

Research activities within this context: I was involved in the implementation of the experimental environment, in order then to explain it to students and support them in the design of experiments. They conducted four experiments to compare different conditions regarding the

performance of participants and their acceptability. The conditions relied on two factors: task complexity and UGV autonomy. The task complexity depended on the number of UGVs to control.

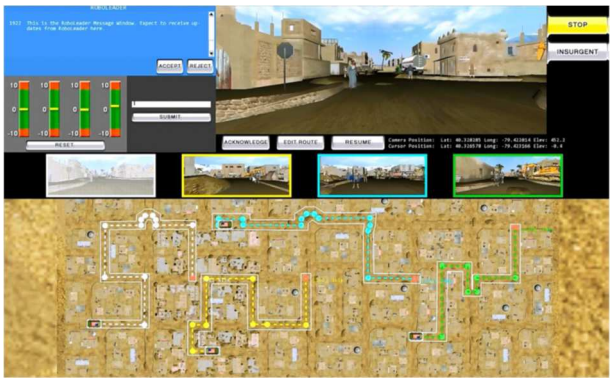

Fig. 76 MIX (The Mixed Initiative eXperimental testbed)

During the first experimental condition, participants defined trajectories to achieve a goal predefined by the experimenters, and they remotely controlled one UGV following this trajectory. During the second experimental condition, participants defined trajectories to reach another goal and the UGV followed this trajectory autonomously. During the third experimental condition, participants defined two different trajectories to reach two different predefined goals. One UGV followed the preplanned trajectory autonomously, and participants remotely controlled a second UGV following the second trajectory. During the fourth experimental condition, participants defined two trajectories, autonomously followed by one UGV. Each experimental condition took place in different areas in order to avoid a learning effect due to familiarity with the environment. Experimental protocol randomly organized conditions in order to avoid a possible learning effect due to the virtual environment and the autonomous UGV use.

Five participants took part to the experiments and results showed that participants' situation awareness was better when they remotely controlled UGVs. This was inconsistent with literature. The number of detected threats was lower with two UGV and there was no significant influence of LoA. Controlling and supervising more than one UGV decreased participants' capabilities and higher LoAs did not compensate task complexity in the way we defined them. Indeed, the relatively short time of each task did not provide enough time to participants to better observe the environment. This empirical study highlighted the relevance of adapting LoAs according to human and autonomous vehicle competences and performance, therefore of designing more useful adaptive LoAs based on Know-How, Know-How-to-Cooperate and task allocation criteria.

Acknowledgments

I would like to thank Sarah Hammiche and Maxime Sédilot for their good work.

7.4.2 Ground robotics in a military context - TAROT

Academic and socio-economic partners: DGA (French acronym for Defense Procurement Agency), THALES OPTRONICS (Land & Joint Systems - Robotics & Mini-UAV Department).

Project: PEA TAROT (French acronym for Advanced Study Programme: Autonomy of decision-making technologies for ground robots) (2006-2009)

Scientific outcomes:

- **1 article in proceedings of international conference with selection committee: [57]**
- **2 reports: [128][130]**
- **3 seminars: [99][115][116]**

Fig. 77 Experimental platform and R-Trooper robot

Scientific Context: The study aimed to define and implement optimal cooperation between a human, for whom we have to define a new job, and a robot partly able to control its trajectory, for which we have to define new cooperative functions. KH and KHC functions were defined (cf. Table 7). During the mission, a human is distant from the operational theater in a command post vehicle, and robot motion is performed on a targeted area. Robot could be partly autonomous according to situations and objectives. Staff officers from a strategic, decisional level plan missions and provide an initial task allocation between the human and the robot at the tactical and operational levels. At the operational level, the objective is to allocate, if possible, the motion control to the robot, deciding which algorithm to use (edge, object and itinerary tracking, safety function), and to allocate information tracked by robot to the human. Nevertheless, when the robot might not be able to be autonomous because of complex environment, the human must take back the control, temporarily or until the end of the mission. The tactical level is more mission-completion oriented in that it is about respecting the plan of the mission. Both the human and the robot have the ability to identify goals and to change from one to another, but only a human can add new goals. A CWS has been designed in order to

inform the human about the robot's goals (geographic point), information analysis carried out by the robot, the choice of the robot's motion algorithm used, and the degree of trust it has in the selected algorithm and in the autonomous mode. Tow displays make up the CWS, and task allocation is the most important information, while other information mainly justifies it (cf. Table 7). We evaluated four LoAs, but whichever the level, human had always the authority to get the control back.

Table 7 Human and robot KH and KHC for LoA identification

	Information acquisition		**Information analysis**		**Decision and action selection**		**Action implementation**	
Know-how								
	Human	**Robot**	**Human**	**Robot**	**Human**	**Robot**	**Human**	**Robot**
Strategic level	Commands / orders		Mission completion		Plan modification		To modify plan	
Tactical level	Current objectives (mobility and reconnaissance)	Current objectives (only mobility)	Goal and object identification for reconnaissance	Next goal	Goals modification and reconnaissance of objects	Goal use or lost	To modify goal	
Operational level	All objects	Objects (edge, target, obstacle)	Trajectory	Choice of its sensorimotor behaviors	Stopping or not the mobility	About stopping or not the mobility	To teleoperate or to stop mobility	To continue or to stop mobility
Know-how-to-cooperate								
Strategic level	Task allocation for all the mission	Task allocation for all the mission	Task allocation analysis according to criteria	Allocation problem	Allocation modification	Allocation modification	To decrease or increase level of autonomy	To decrease level of autonomy
Tactical level	Robot behaviour	Object to use as goal	Robot behaviour analysis according current or new goal	Problem with current goal	New goal to add in the plan and robot behaviour to change or to learn	Selection of next goal	To provide information concerning new goal	To choice next goal or to ask information
Operational level	Using robot sensors	Feedback about sensorimotor behavior	Robot behaviour according to trajectory	Information human operator can't have		Use of new sensorimotor behavior and obstacle		To provide information concerning trajectory

Interesting results demonstrate the usefulness of the methodological technique, the Wizard of Oz, as well as the way we defined of LoAs. Participants provided also important points about task allocation and sharing control, especially regarding their cooperation with human teammates today, highlighting their mutual understanding and team awareness.

Research activities within this context: I was involved in the design of robot and CWS using the model of cooperative agents' interactions to identify current KH and KHC of each agent, with the assistance of Thalès engineers who knew the capabilities of robots they designed well. Two experiments were conducted in two different areas (simple vs. complex) and with two different experimental controls (with vs. without Wizard of Oz). The first experiments aimed to evaluate the benefit of using autonomous robots, and the human had no other objective other than respecting the trajectory. During the second experiment, the human had the objective of doing reconnaissance by searching for objects in the environment in addition to the previous

task. Only the human was able to perform the reconnaissance task. The missions took place within Thales group infrastructures for the first experiment and on an industrial wasteland for the second. The first one was limited to be easier for the robot to perform task; the second one had several sparse areas of vegetation and debris from a destroyed factory, to provide several potential obstacles.

As for the main results, the human always felt the need to validate the allocation of control to robot even if it was not necessary, in order to check everything was in order before agreeing robot autonomy. Whatever the selected LoA, participants seemed to have more confidence in the robot during the first experiment than in the second. Indeed, the second experiment imposed reconnaissance tasks, which forced participants to have less time to supervise robot even though this task was dependent on robot motion. A lack of coordination between decision making and action of each agent at the operational level can impact trust. The increase of the robot's KHC might solve such a problem. Another explanation for the greater level of trust in the first experiment is the use of Wizard of Oz method. This technique allows technical problems, such as losing a target because of fog or rain, to be avoided. Moreover, robot motion and decision seemed to be more "human-like" than when we used programmed algorithms. As perspectives, during debriefing, participants underlined the importance of preparing the mission plan themselves and thus deciding task allocation according to their own task allocation criteria.

Acknowledgments

The present research work was supported by the French Defense Procurement Agency and coordinated by THALES OPTRONICS (Land & Joint Systems - Robotics & Mini-UAV Department). I gratefully acknowledge the support of these institutions.

7.4.3 Ground robotics in a crisis management context – SUCRé

Academic and socio-economic partners: Ecole Nationale Supérieur des Arts et Industries Textiles (GEMTEX), Université d'Artois (LGI2A), Université de Lille 1 (previously LAGIS, now CRYSTAL), Ecole des Mines de Douai (URIA), Université de Reims Champagne Ardenne (CRESTIC), Université de Technologies de Troyes (Tech-CICO and LM2S).

Project: Regional project SUCRé (the French acronym for Identification, design and evaluation of technological tools to support cooperative activities of several actors involved in crisis management: Human-Human and Human-Robots Cooperation in hostile environment) (2014-2017).

Role: Co-supervisor of Lydia Habib (PhD) with P. Millot, and supervisor of S. Boulnois (Engineer)

Scientific outcomes:

- **4 articles in proceedings of international conference with selection committee: [29][33][35][39]**
- **2 book chapters: [19][20]**
- **4 reports: [119][120][121][122]**
- **2 seminars: [103][105]**

Scientific Context: The project dealt with the design of methodological and technological tools for the management and control of crisis for French Department Fire and Rescue Service, with an original and multidisciplinary approach. The project dealt with sociotechnical systems such as military organization or civil security. They manage crises, taking advantage of cooperation between command structures, human operators in the field and all available resources. The use of automation offers opportunities to better exploit information to improve understanding, decision-making and tempo, as well as supporting headquarters for more agile command and control. Among these resources, in hostile environments, mobile robots may prevent human operators from being exposed to danger. These robots can have cooperative abilities in order to increase the efficiency of such a sociotechnical system. Therefore, the focus of the project is the study and design of assistance systems able to support Human(s)-Robot(s) cooperation inside sociotechnical systems, and complex and dynamic environments. Furthermore, robot-robot cooperation based on a self-organized swarm has to reach objectives ordered by the crisis unit. A remote human operator manages tactical tasks from a command post vehicle according to the mission plan provided at the strategic level, which here is conducted by a crisis unit.

The remote human operator supervises the swarm supported by assistance systems to manage humans' and robots' task allocation in case of unexpected events from the operational level or

new objectives from the strategic level. Other aspects of cooperation were studied but not evaluated, namely the cooperation between human and robot through smart clothes. Technical points were defined and implemented, and robot was able to use data about a human (temperature, fall...) in order to alert other humans and to stay close to human to facilitate visual/audio communication if necessary.

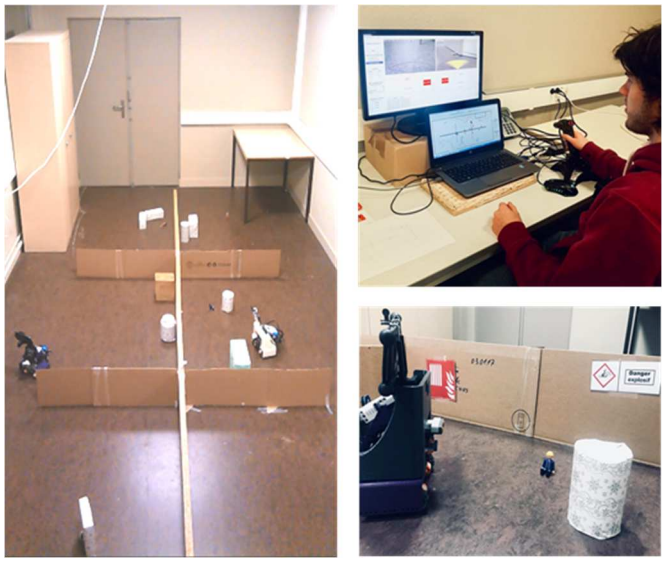

Fig. 78 Experiments to evaluate Humans-Robots cooperation in crisis management

Research activities within this context: I was involved in the conceptual aspects about methodology and cooperation definition, as well as in the development of the experimental platform for crisis management. We conducted experiments to evaluate three LoAs defined according to KH and KHC functions allocated to humans and/or robots. At the operational level, the mission (task) of the human-robots team dealt with obstacle detection and avoidance, path planning and tracking, and reconnaissance mapping. They were sharable tasks, except for the reconnaissance mapping subtask because robots were not equipped for image processing. At the tactical level, the interface focused on the mission plan, the robot positions in real time, and the human operator's reconnaissance mapping regarding the localization of victims and dangers (risk of fire, risk of explosion, toxic material and gas valve). Eighteen participants took part in the experiment, with varying degrees of training in video games and the control of robots. We conducted two experimental conditions different according to the complexity of the environment (visibility, density of obstacles, hypothesis for number of victims and dangers) displayed on the map or not. Subjective measures dealt with human operator workload (assessed through Nasa Task Load) and human operator Situation Awareness. Objective measures dealt with human operator performance based on the number of located victims and dangers, and the time required to fulfil the mission.

Acknowledgment: The project SUCRé was partly funded by the Regional Council of the French Region “Hauts de France” and supported by GRAISYHM programs. We gratefully acknowledge these institutions and the Nord-Pas-de-Calais department Fire and Rescue Service for the time they spent explaining their activities and for the opportunity to observe training sessions of firefighters, especially Commander Laurent Foucrier and Commander Eric Mareschi. I would like to thank GEMTEX lab of ENSAIT for our very pleasant and fruitful collaboration.

7.4.4 Ground Robotics – Handicap

Academic and socio-economic partners: University College of London

Project: Project conducted within the framework of the visiting professor application with Tom Carlson (2016-2018)

Role: Co-supervisor of Lydia Habib (PhD) with P. Millot.

Scientific outcomes:

- **2 articles in proceedings of international conference with selection committee: [32][24]**

Scientific Context: The project had the objective of providing people who have lost motor or sensory capabilities with assistance systems to enable them to communicate with others and interact with their environment. The only way to communicate for such people might be to use brain signals directly. The goal is therefore to provide people with tetraplegia, confined to their room, with a telepresence tool that facilitates the daily interactions so many of us take for granted. In our case, the telepresence tool is a robot that is remotely controlled. The system is therefore composed of a BCI and a visual interface to implement an "emulated haptic shared control" of the robot (cf. Fig. 79). The aim is to share motion control between the human and the robot according to the difficulty of the situation. We implemented two layers of cooperation. At the operational layer, the user and the robot have to focus on obstacle avoidance. The human can detect obstacles thanks to a live video stream of the environment from the robot's perspective; and the robot can detect obstacles thanks to its actuated ultrasonic sensor (shared information gathering and analysis). Both can make decisions (shared decision), but only the robot can apply the decision by modifying its trajectory. The tactical layer manages modifications to the mission plan, *i.e.* how to modify the trajectory to reach the target, after the avoidance of an unexpected obstacle. However, in this case of telepresence, we consider that the target does not impose the design of a precise plan, because it could be changed as and when different opportunities arise for the human (new information to search, other people to meet...). Moreover, it could be difficult for the human to provide precise details of the target to the robot, due to the relatively low resolution and throughput of the BCI as an interface. In this case, the robot is not able to know the target explicitly and to modify the trajectory itself to reach it.

Both human and robot detect and manage interference in obstacle detection and command through the Common Work Space that implements the "emulated shared control". The final decision concerning the command to be executed (right or left) is made by the robot, due to the human's limited capacity to react quickly to a situation. The idea is to emulate haptic behavior based on muscles effort 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 and this is conveyed to the user through our standard visual feedback.

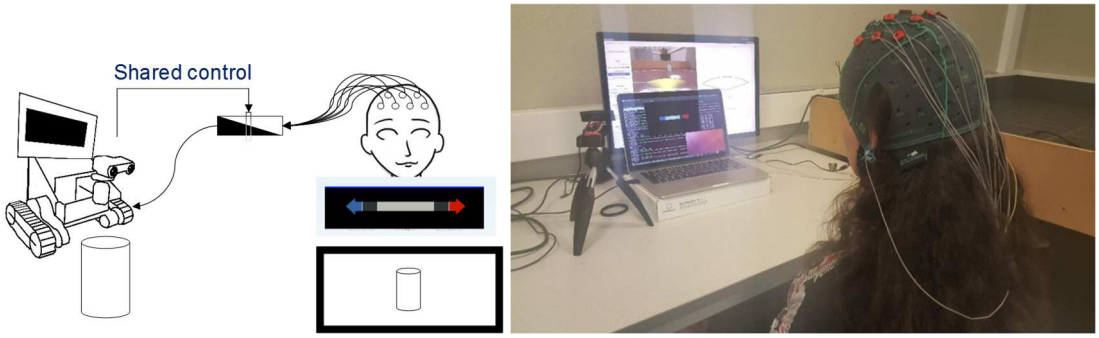

Fig. 79 Human-BCI-robot cooperation - Shared control with "emulated haptic feedback"

The user moves the grey bar to the left and right by performing motor imagery (cf. Fig. 79: Grey bar between the red and blue arrows). When the bar hits one of the arrows, it delivers the corresponding turn left or turn right command. Dynamically changing the thresholds to deliver BCI commands is illustrated by changing the size of the arrow and essentially makes it (mentally) easier or more difficult to turn in one or both directions.

Research activities within this context: I was involved in the conceptual aspects of the "emulated haptic feedback", as well as in the development of the experimental platform composed of the robot, visual interface and BCI. We conducted two experiments, the first to test the technical feasibility and the second to test the concept. During the experiments, the participants had to control the robot in order to follow the trajectory indicated by the white tape on the floor, whilst avoiding obstacles. The robot is not able to follow the set trajectory because it does not know it, just as it would not know where a user would like it to go with a remote control. The users, who were not disable people, had to keep their hands relaxed loosely on their lap and only have to imagine the kinesthetic movement of their left or the right hand. Two experimental conditions have been defined, combining the possibility to use emulated haptic feedback or not. Results showed that with the "emulated Haptic feedback", the mean number of collisions is smaller and the robot makes fewer stops, perhaps because it is more difficult for the participant to send the robot in a direction where there is clearly an obstacle. On average, users complete more "correct" sections of the trajectory. In future studies, we would like to give more assistance to the human operator by adapting dynamically the behavior of the robot according to the human's state. In fact, we assume that such a task required a high level of concentration and mental workload.

Acknowledgment: We would to thank Tom Carlson and Nadia Sciacca for their venue in Valenciennes and their involvement in the experiments.

7.5 Manufacturing systems

An objective of the Industry 4.0 and the factory of the future is to reach a high level of mass customization, low level of energy consumption through more agility in the global manufacturing system. Such a demand implies designing a more flexible and more resilient manufacturing system. One way is to involve new technologies from digital and manufacturing technology fields. Nevertheless, at the same time, humans must be kept at the center of the global process for decision making and control. Indeed, Intelligent Manufacturing Systems (IMS) tend to implement new autonomous systems, nevertheless so autonomous that humans could be less and less aware of plant and controller states. Such lack of human situation awareness can lead to poor IMS performance. Indeed, Humans are the ultimate agent to manage unforeseen problems or situations not managed by the automated part. Hence, it is necessary to design human-centered supervisory control tools for IMS, taking advantages of human capabilities.

The following projects deal with these objectives and aim to design IMS with the Human-Machine Cooperation approach.

7.6 Manufacturing Systems – Diagnosis Assistance System

Academic and socio-economic partners: University of Reims (CReSTIC), Nancy (CRAN UMR CNRS 7039).

Project: GIS 3SGS ADEXEC (Approach to Detect and EXplain Errors of Command) (2007-2012)

Scientific outcomes:

- **1 article in a national journal: [14]**
- **3 articles in proceedings of international conference with selection committee: [48][54][48]**

Scientific Context: This project took place within the framework of the GIS 3SGS project (the French acronym for Scientific Interest Group – Systems Monitoring, Dependability and Security). The main objective of the project is to support the diagnosis of a command implemented to control a process, which might not be suitable anymore because maintenance workers or production workers have modified it due to technical problems or new production goals. We placed inside a PLC (Programmable Logical Controller), so independent to the command, a robust filter based on safety constraints and forbidden states identified by experts and validated by model checking. Therefore, the filter was able to detect dangerous forbidden states of the process and stop it. This approach maintains process safety by avoiding damage to products and manufacturing system. Nevertheless, the filter's decision to stop a process may suppress important information that human operators might use to diagnose and correct the command. Therefore, we complemented the implementation of the filter with assistance systems that provide four levels of explanation to human operators to diagnose command errors.

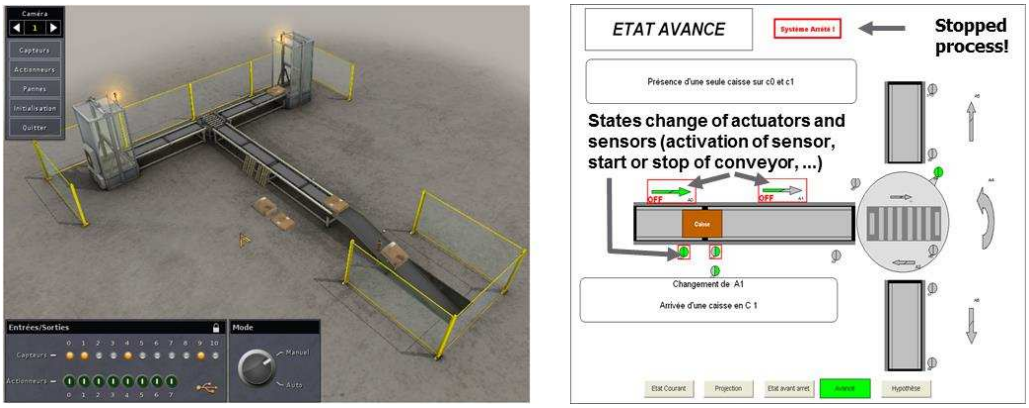

Fig. 80 Experimental platform: ITS-PLC to simulate the operative part of the process (on the left) and the assistance system (on the right) providing explanations about process stop and command errors

We conducted experiments and the general trend was that the more the assistance system provides explanations about its analysis of the process, i.e. if participants have more explanations than just current and projection views, the more they detect and correct the error in the command. Nevertheless, more precise the levels of explanation would require more difficult and time-consuming design. Designers must therefore find a compromise.

Research activities within this context: Conceptual aspects about the identification of levels of explanation were the main focus, as well as the design and management of experiments. We defined four levels of explanation, based on the concept of human-machine cooperation, to assess the adaptation of the level of explanation according to the type of human operator who would have to diagnose, *i.e.* according to their expertise and experience with the process. We created new interfaces with a "top view" of the process showing sensors and actuators, and information according to the levels of explanation, as well as for the "current view", displaying sensors and actuator states at the stopped time. The first level of explanation dealt with the "projection view", that is, what would have been the state of the process if the process had not been stopped by the assistance system, or in other words, negative consequences due to command error. The second level of explanation, "status before stop", is the presentation of the state of the process just before it was stopped. This level of explanation focuses on the process elements that had triggered the filter and presents the result of the erroneous command. The third level of explanation, "advanced representation", is the presentation of the events (rising and falling edge) which had reached a forbidden process state. Here, the display presents two process states, before the forbidden state and after, and explains the undesirable behavior of the command. The fourth level of explanation is the presentation of hypotheses concerning the command errors. This level explains the behavior that the command should have, and presents information concerning the non-use of information to reach an output, or the explanation of unwanted output. Nine participants took part in the experiments. Objective data stemming from command error detection and solving, and subjective stemming from answers to questionnaires provided the results previously presented.

Acknowledgment: Special thanks to Pascale Marangé, Alexandre Philippot and Bernard Riera for our close cooperation.

7.6.1 Manufacturing Systems – Supervision and control of Self-organized system

Academic and socio-economic partners: Master's students

Project: Master's students project (2013-2015)

Role: Co-supervisor of Thomas Laurain and Sébastien Boulnois (Master's students).

Scientific outcomes:

- **1 article in an international journal: [3]**
- **2 articles in proceedings of international conference with selection committee: [37][45]**
- **1 report: [118]**

Scientific Context: The objective of this study was the design of a manufacturing system able to take advantage of available intelligence systems technologies while keeping human skills and competences globally in control. The idea was to evaluate the impact of human-machine cooperation on manufacturing system performance compared to a techno-centered design. The system studied within this framework was based on the specific artificial self-organizing intelligent control for a flexible manufacturing system (FMS). Artificial self-organizing (ASO) systems are a possible way of implementing IMS principles. They have been selected for their potential reactivity in the face of disturbances, including human intervention.

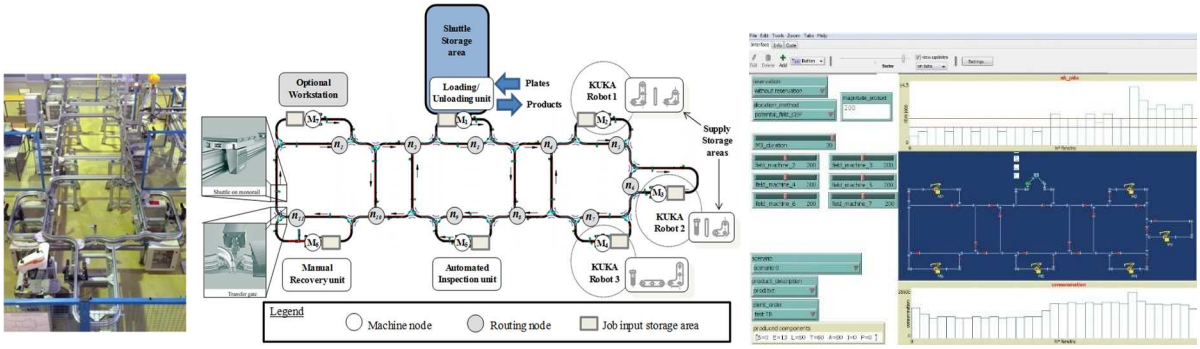

Fig. 81 Flexible manufacturing system at Université Polytechnique Hauts-de-France (AIP-PRIMECA FMS) – Emulated system – CWS with the tactical assistance

The suggested ASO manufacturing control system, based on holonic and bio-inspired paradigms is a pure techno-centered approach. The problem is that since the ASO system is self-organized, then it may behave in an unexpected way, leading to, at the very least, poor performance, but also potentially disruptive or hazardous situations. This prompted us to re-consider the potential benefits of a human operator because of their ability to react to the unpredictable and to spontaneously conceive solutions. However, the behavior of the ASO is highly reactive and hard to predict for humans, thus a human-centered approach was considered

within the framework of the HMC principles. Instead of focusing on the ASO at the operational level, we also analyzed tactical and strategic levels to provide human with assistance systems (cf. Fig. 82). At the tactical level, the human has to supervise and, if necessary, update the manufacturing plan progress controlled by the ASO. Nevertheless, ASO systems are complex and highly reactive systems that humans may have difficulty understanding and manage without stopping the process. In order to avoid such an extreme situation, a tactical assistance system, linked to ASO system, enables the testing of possible decisions.

Research activities within this context: I was involved in the conceptual aspects regarding the increase in KHC of the IMS to support humans in its understanding and control. I was also involved in the supervision of the Master's students who designed and conducted experiments. Subjective data recording dealt with workload evaluation through online and offline (NASA-TLX) questionnaires. We calculated objective data according to the expected performance of the manufacturing system. The goal was not to maximize the throughput but to maintain it between a lower limit (set to 4 products/300s) and an upper limit (set to 6 products/300s). Keeping the throughput constrained helps to maintain control over energy consumption, for which a maximum level was set to 20 kWh. We compared — performance without human in the loop, *i.e.* techno-centered approach, — performance with human in the loop but without the tactical assistance system, — and performance with human in the loop assisted by the proposed tactical decision assistance system *i.e.* human-centered approach. When in the loop, the human was aware of process states and acted to reach requested goals. Nevertheless, without the suggested tactical decision assistance, the human was unable to maintain the indicator within the limits, as the number of products and thus the energy consumption threshold exceeded. Therefore, the best results were obtained when the human was involved and assisted. Results stemming from the online and offline questionnaires showed a decrease in the mental demand thanks to the help provided by the assistance system to anticipate the future ASO behavior, an increase in self-confidence and trust in the assistance system, and a decrease in effort because the assistance system performs part of the task.

Acknowledgment: I would like to thank Thomas Laurain and Sébastien Boulnois for their excellent work.

7.6.2 Manufacturing Systems – Humans-Intelligent systems Cooperation

Academic and socio-economic partners: Université de Reims Champagne Ardenne (CRESTIC), Université de Bretagne-Sud, Lorient (Lab-Sticc)

Project: ANR HUMANISM (HUman-MAchines cooperatioN for flexIble production SysteMs) (2017-2021)

Role: Co-supervisor of Quentin Berdal (PhD) with D. Trentesaux and C. Chauvin.

Scientific outcomes:

- **4 articles in proceedings of international conference with selection committee: [17][27][28][31]**
- **3 seminars: [100][101][102]**

Scientific Context: The objective of this project is to propose a methodology for designing cooperative systems to support human operators of the Factory of the Future by maintaining their situation awareness and providing adapted assistance systems to make decisions and to manage uncertainties. The Human-Machine cooperation approach, reinforced by the Cognitive Work Analysis approach and the Diagnosis approach, aim to design levels of automation adaptable to self-organized systems, suitable to human needs, and despite the increase in systems complexity and the on-going quest for production systems performance. We are studying three use cases: Human-Robots-ASO cooperation, Humans-Cobot cooperation and Human-Diagnosis support system cooperation (cf. Fig. 82). The use cases are complementary examples of human-machine cooperation that exists or may exist soon in Industry 4.0. They focus on the operational and tactical layers of cooperation. Each agent involved in each layer is in cooperation with all agents of the layers involved in the control of the process. The combination of all individual and cooperative abilities of agents may handle the ethical risks and lead to the best organization between them.

Fig. 82 Human-Robots-ASO cooperation, Université Polytechnique Hauts-de-France – Humans-Cobot cooperation, Université Bretagne-Sud, Lorient – Human-Diagnosis support system cooperation, Université de Reims

Research activities within this context: My activities focused on the link between Human-Machine cooperation and Cognitive Work Analysis approaches, especially the study of their complementarity and how they can be combined to increase the capacity of the design methodology. We identified possibilities that were implemented for a use case dealing with the control of a production cell, loaded and unloaded by ground robots with two levels of automation. We evaluated assistance systems to supervise and control the production cell, the robots and their interactions. Experiments took place with participants with different levels of expertise and experience regarding manufacturing systems and robotics.

Acknowledgment: The research presented in this paper was carried out in the context of the HUMANISM N° ANR-17-CE10-0009 research program, funded by the ANR "Agence Nationale de la Recherche". I gratefully acknowledge the contribution of this institution.

7.6.3 Manufacturing systems – Industry 4.0 in Garment factory

Academic and socio-economic partners: École Nationale Supérieure des Arts et Industries Textiles (GEMTEX lab), Camaïeu (French retail-clothing company)

Project: Smart Fashion 4.0 (2019-2022)

Role: Co-supervisor of Mehran Majidan (PhD) with F. Vanderhaegen and S. Thomassey

Scientific Context: The project aims to tackle limits of retail-clothing company still based on international supply chains and with long delays to market standard products, while consumption patterns are changing and online sales are booming. The project's objective is to decrease of design and production time for the fashion and luxury goods sectors. New technologies are being studied and will be proposed to respond to this objective. Assistance systems may support managers in the selection of the products regarding the short-term and medium-term trends of consumers. Big databases, virtual shops, virtual prototypes may be used to identify new products. Assistance systems may support manufacturers to make decisions regarding humans-machines organizations that would be adapted according to types of products, human and machine competences and capacities. Adaptable organizations would be evaluated according to human acceptability and performance.

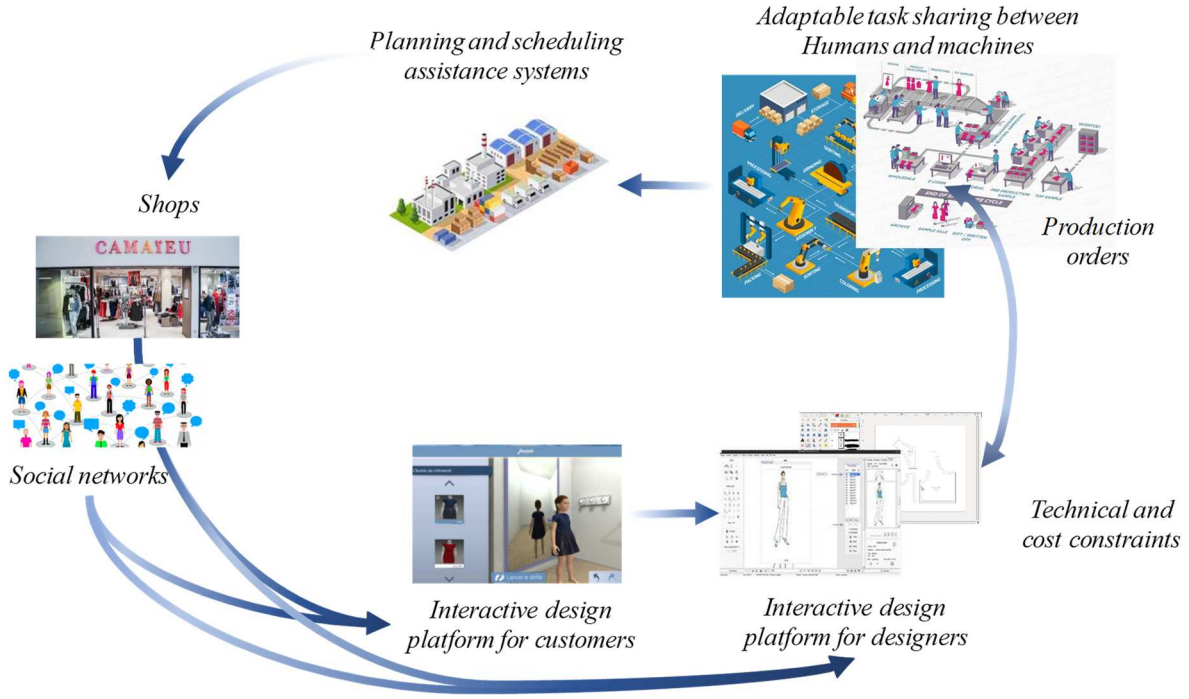

Fig. 83 Industry 4.0 in textile-clothing chain

Research activities within this context: The research will focus on the improvement of methodology supporting the design and evaluation of adaptable human(s)-machine(s) organization. The methodology will take into account the current ability of machines to manufacture clothes and the current ability of human operators at several decisional levels in order to extend such abilities to perform new functions and to cooperate with each other. New jobs, and so new professional training opportunities, will be created. Such a methodology may help identify and evaluating new humans-machines organizations and task allocation according to objectives and constraints provided by managers. These organizations will be then implemented on one production line of Camaïeu, partly to test the feasibility, but mainly to test the benefit of using the method, the new organizations and their impact on global performance and human acceptability.

Acknowledgment: I would like to thank Xianyi Zeng, Ludovic Koehl, Sébastien Thomassey, and Guillaume Tartare from ENSAIT – GEMTEX for their friendly cooperation which continues to grow.

7.7 Railway

Academic and socio-economic partners: Railenium, SNCF, Thales C&S, Actia Telecom, CNES

Project: TC-RAIL project: Train remote control (2017-2021)

Role: Co-supervisor of Quentin Gadmer (Research engineer in Railenium) with Philippe Richard

Scientific outcomes:

- **1 article in proceedings of international conference with selection committee: [25]**

Scientific Context: Levels of automation implemented in the railway domain are already high, especially with the use of automated metro systems. Four Grades of Automations (GoA) have been defined. Automatic Train Protection (ATP) systems define GoA1 and are under the control of the train driver. GoA2 is distinguished by the implementation of ATP complemented by the Automatic Train Operation (ATO) system, while still remaining under the control of the train driver. GoA3 is the driverless control grade, and finally GoA4 is the unattended train (UTO). Nevertheless, high levels of automation in the urban sector cannot be directly transposed to train control in mainline or freight sectors, since the train driving environment is more likely to face various unexpected events. The autonomous train is still the final objective, nevertheless before reaching such a high level of automation, the first step will be to design intermediate levels where a human operator is kept "in the loop" of the control of the train. As for the scope of the TC-Rail project, the development of remote driving is a necessary first stage that serves two objectives: the optimization of "last kilometers" for freight railway traffic and a way to recover control from an autonomous train, as a degraded driving mode.

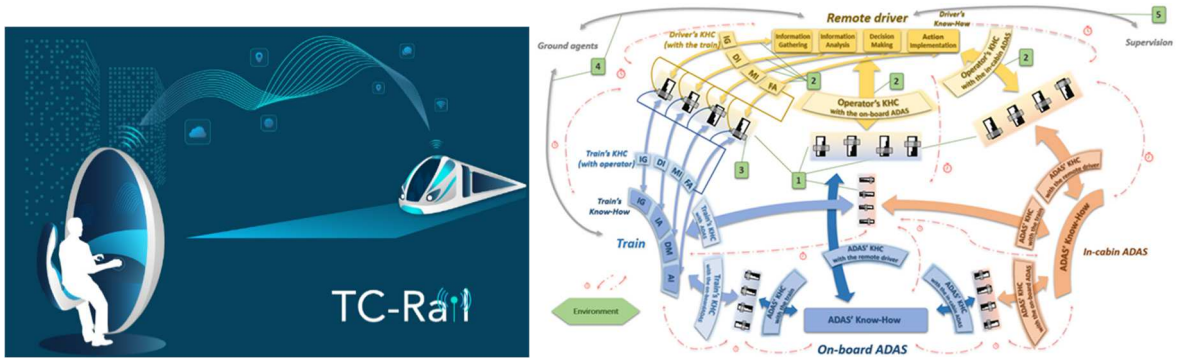

Fig. 84 Remote control of train and human-ADASs cooperation

Research activities within this context: Railway literature rarely addresses these topics as remote driving may lead to highly risky and complex situations. Therefore, the first goal is to identify how such risks can be addressed through a Human-machine cooperation approach. Literature and several studies dealing with remote control point out that, due to the loss of most of the proprioceptive information, cognitive workload may increase, and perception, attention and sense of presence may decrease. For this reason, a state of the art analysis on cognitive mechanisms in railway driving was conducted, completed by an activity analysis of railway driving activities (Anceaux, Mouchel, Paglia, & Richard, 2018). Since new systems must be adapted to current trains and infrastructure, we propose to design three types of system to support remote train drivers in the control of the train. The first one deals with train driver work position mainly based on a human-machine interface allowing the remote control of the train with the digital representation of devices currently used in the train cabin. Therefore, this work position provides a video feedback to the driver and the usual screen control and command devices. The second system augments the work position by providing tools for information gathering, information analysis, decision making and action, *i.e.* to support the KH of the driver. Moreover, the second system may support the driver KHC by managing cooperation with the train, but also with other human agents involved in the traffic management. Indeed, the train driver will be cut off from the usual human agents such as ground agents (from the train station or technicians operating on the train after an incident), rail traffic controllers and other drivers.

Acknowledgment: I would like to thank Quentin Gadmer for his excellent work.

Chapter 8. Appendix 2

Publications in which I was involved as first author or co-author.

8.1 International journal

[1] Flemisch F., Abbink D., Itoh M., Pacaux-Lemoine M.-P., Wessel G. (2019). Joining the blunt and the pointy end of the spear: towards a common framework of joint action, human–machine cooperation, cooperative guidance and control, shared, traded and supervisory control. Cognition Technology and Work, 21 (4), pp. 555-568 [DOI=10.1007/s10111-019-00576-1].

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8.2 National journal

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8.5 Book chapter

[19] Tartare G., Pacaux-Lemoine M.-P., Koehl L., Zeng X. (2019). Développement d'un vêtement intelligent pour l'aide à la gestion de crises - application au contrôle d'incendies. In F. Vanderhaegen, C. Maaoui, M. Sallak, D. Berdjag, Défis de l'automatisation des systèmes socio-techniques, ISTE éditions, pp. 300-317, ISBN 9781784055394

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8.6 Proceedings of International Conference with selection committee

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