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Modular Human–Robot Applications in the Digital Shopfloor Based on IEC-61499

Franco A. Cavadini[1] and Paolo Pedrazzoli[2]

[1]Synesis, SCARL, Via Cavour 2, 22074 Lomazzo, Italy
[2]Scuola Universitaria Professionale della Svizzera Italiana (SUPSI), The Institute of Systems and Technologies for Sustainable Production (ISTEPS), Galleria 2, Via Cantonale 2C, CH-6928 Manno, Switzerland
E-mail: franco.cavadini@synesis-consortium.eu; paolo.pedrazzoli@supsi.ch

This chapter presents the results of the conception effort done under Daedalus to transfer the technological results of IEC-61499 into the industrial domain of Human–Robot collaboration, with the aim of deploying the concept of mutualism in next-generation continuously adaptive Human–Machine interactions, where operators and robots mutually complement their physical, intellectual and sensorial capacities to achieve optimized quality of the working environment, while increasing manufacturing performance and flexibility. The architecture proposed envisions a future scenario where Human–Machine distributed automation is orchestrated through the IEC-61499 formalism, to empower worker-centred cooperation and to capitalize on both worker's and robot's strengths to improve synergistically their integrated effort.

8.1 Introduction

Personnel costs in Europe are higher compared to other industrial regions; hence, EU industry today competes in the global market by offering high added-value products. This is possible thanks to the extreme qualification level and know-how of its 17 million shopfloor workers.

To keep this true, European manufacturing industry needs to adopt a new production paradigm, focusing on processes where robots collaborate with humans with mutual benefits in terms of skill growth and support. The problem is that current automation approaches in Europe have disregarded the importance of added value of workers, enhancing de-skilling of European workforce and labour shedding.

Future European value-adding manufacturing industries will have to rely more and more on the virtuous combination of machines and operators [1], to increase the standard of quality of their shopfloors while remaining competitive with low-wage countries. To exploit new synergies between operators and machines, future manufacturing processes will have to exhibit a dynamically reconfigurable overall behaviour, through continuous physical interactions and bidirectional exchange of information between them.

A possible solution towards a comprehensive management of this highly integrated collaboration, by pushing the boundaries of the topic of human–robot Mutualism, is to apply the IEC-61499 standard to orchestrate their joint behaviour.

In fact, in collaborative tasks, the overall dynamics of the interactions between a robot and a human is currently an emergent property that implicitly arises from their individual behaviours. On the contrary, the aim should be of making these implicit properties explicit, by representing, standardizing and orchestrating the overall dynamics of human–robot interaction. Achieving human–robot mutualism through such orchestration will dramatically improve the transparency and acceptance of robots for users, as well as substantially increase the ergonomy and efficiency of collaborative tasks.

The main bottleneck in orchestration for mutualism is that current scheduling and planning algorithms, powerful as they may be, are limited by the expressiveness and fidelity of the representations they operate upon. Therefore, the need of the market (partially tackled in Daedalus) is to develop and standardize such representations for open manufacturing processes and ensure their compatibility with existing norms, with the IEC-61499 standard for industrial distributed automation being the cornerstone. This can be achieved only by working on three high-level objectives:

- Standardizing and homogenizing the way intelligent agents, both human and robotics, are represented and orchestrated, from design to runtime stage, in a team with multiple dynamically varying objectives;

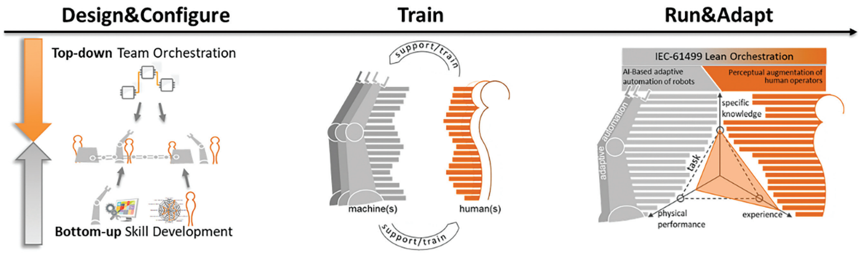

Figure 8.1 Life-cycle stages to achieve human–robot symbiosis from design to runtime through dedicated training.

- Engineering a new generation of mechatronic intelligent devices for human–robot collaboration, to facilitate and augment bidirectional interactions with operators while exhibiting inherently safe behaviours;
- A widespread application of AI-based techniques, from semantic planning for orchestration and task planning to deep learning for human intent recognition. Applying AI at different functional levels and life-cycle stages is essential to go beyond current rigidity of robotics systems and, thus, to increase by-design compatibility with human operators.

What European manufacturing processes need is a more effective and extensive symbiosis between humans and robots in the work environment, achieved by proposing new technological solutions but also reshaping the way those processes (and the systems executing them) are conceived, designed, run and reconfigured (Figure 8.1).

8.2 Human and Robots in Manufacturing: Shifting the Paradigm from Co-Existence to Mutualism

European manufacturing industry, with more than 2M enterprises that employ 30M people, must face two main challenges: (i) reduction of product life cycles, with a corresponding reduction in the amortization time for the investments; (ii) increase of customization from the market, that requires flexibility [2] and adaptability for manufacturing smaller batch sizes with constant product changes [3]. EU industry therefore competes in the global market by offering high-quality products, thanks to the high qualification level and know-how of its 17 million shopfloor workers. Sustaining it requires to maintain as much time as possible these high skilled workers, postponing their retirement age and ensuring a smooth transition by incorporating younger workers. However, the negative impression of manufacturing due to its negative impact on health [4] and low attractiveness (monotonous and boring work), combined with the aging of European population, will provoke a lack of qualified shop floor workers in 2030 [5].

The problem is that current automation approaches in Europe have disregarded the importance of added value of workers, enhancing de-skilling process in European workforce and labour shedding [6]. However, Japan, one of the key manufacturers of robotics, has shown that other manufacturing models where robots and technologies support and improve worker, instead of substituting them, are possible [7].

As explored in the literature and in previously approved EC-funded projects (e.g. MAN-MADE [8]), the workplaces of the future are expected to be worker-centric (as opposed to task-centric), with an increased role of workers in pursuing production performances and personal well-being. In this new paradigm, it is the task that suits skills, experience, capacities and needs of the worker, here turned from a passive constraint to a variable opportunity. Previous research and pilot implementations have in fact demonstrated that collaborative human–robot workspaces, knowledge networks and augmented reality support [9] can improve productivity and workers' well-being, reducing 50% the time of first time assembly [10] or bringing near novice workers to experienced ones [11].

The paradigm of human–machine symbiosis suggested by Tzafestas [12] and revised (with a focus on assembly systems) in Ferreira et al. [13] appoints advanced human–machine symbiotic workplaces as the foundation for human-centric factories of the future.

Ultimately, such a positive and human-centric vision still lacks in actual instantiations. The reasons are several:

- A new conceptual framework, intended to deploy symbiotic human–robot ecosystems, needs to be created for the manufacturing environment, effectively describing workers, intelligent machine and, especially, their interactions and collaborative tasks;
- Advanced algorithms and tools based on artificial intelligence are missing to "augment" the mutual perception and understanding of the behaviour of robots and operators, for an effective synergistic approach in executing joint tasks;

- Trust-creation environments, where human–machine team can orchestrate their respective actions in a controlled situation and where machines are aware of not only the human worker's physical but also mental state. In fact, human–machine interaction is usually conceived in one way, with one of the elements providing and the other receiving support;
- Worker-centric human–machine symbiotic interaction in real industrial environments is currently limited by available legislation (e.g. EU Machinery Directive 2006/42/EC, ISO 10218 standard) and insufficient empirical data, so that only sequential and parallel cooperation as forms of co-work are possible;
- Configuration of human–machine interaction is currently performed at its setting-up and, then, seldom updated. But human operators (and, just partially, machines) modify their behaviour and mood daily: a manufacturing symbiosis needs to be constantly adapted and tuned, considering actual symbionts' behaviours;
- A unified definition of what is "good" for the worker still lacks: a new approach combining subjective and objective measures is needed for this evaluation.

8.3 The "Mutualism Framework" Based on IEC-61499

Advanced human–machine interaction is the most promising approach to enable worker-centric manufacturing in the factory of the future. Some authors [13, 15] have recently suggested the implementation of a "symbiotic system" paradigm, where human and robotic operators cooperate for an effective accomplishment of manufacturing tasks.

What has been conceived aims at embracing this approach and proposes a more complete and concrete interpretation based on the biological concept of Mutualism, a peculiar relationship between two organisms of different species where each individual benefit from the activity of the other. Mutualism is a specific instance of symbiosis, establishing a win–win interaction.

This paradigm is adopted as basis for an innovative methodological framework that supports the effective integration and implementation of collaborative robotics technology over the life cycle of the plant, from conceptual stage to runtime and re-configuration. The objective is to sustain a deeper and more extensive collaboration between humans and robots, as intelligent agents orchestrated to achieve dynamically varying objectives, while mutually compensating for their limits through their respective strengths.

Members of this orchestrated manufacturing team are called symbionts and they are either humans or robots/intelligent devices. Regardless of their nature, symbionts are all able to provide and receive support (i.e. giving or receiving a quantifiable benefit thanks to their interaction).

Symbionts are intended to operate in real manufacturing environments, and the effectiveness of their Mutualism is assessed continuously (from design to runtime) considering a holistic worker-centric perspective of "well-being" and psychological safety. Clearly, Symbionts are "living" entities (both humans and robots) in that they adjust their behaviour on a task-wise basis and modify their performances according to changing exogenous elements.

These qualitative characteristics result in the following concepts composing the so-called "Mutualism Framework".

8.3.1 "Orchestrated Lean Automation": Merging IEC-61499 with the Toyota Philosophy

When dealing with classical industrial automation use-cases, a core concept is the real-time orchestration of automation tasks – provided by various subsystems, machines or robotic manipulators – to guarantee the exact execution of a well-specified behaviour, usually within the constraints of a time cycle. On the other hand, complex production processes, especially where the intervention of highly qualified human operators is essential, have been optimized throughout the last decades with the lean manufacturing approach, mostly under the Toyota philosophy.

For a more holistic integration of humans and robots, it has been introduced the concept of hybrid orchestration (at runtime stage) of IEC-61499 automation tasks executed by both types of Symbionts but framed in a lean methodological and engineering context (in the design stage). The synthesis of these two elements (Figure 8.2) requires adaptation and evolution of both, where orchestration will have to consider the inevitable variability (and, partly, unpredictability) of human tasks (thanks to the support of artificial intelligence), while the lean concepts will have to be extended considering the very peculiar capacities of intelligent mechatronic systems.

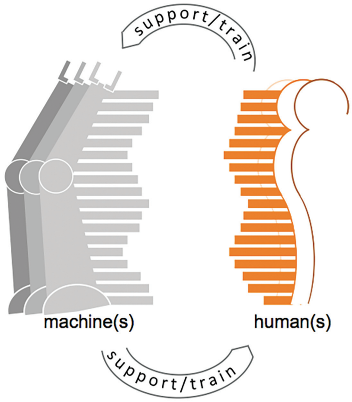

Figure 8.2 Bidirectional exchange of support between humans and robots.

8.3.2 A Hybrid Team of Symbionts for Bidirectional Mutualistic Compensation

Latest studies [13, 15] addressing human–machine interaction propose to establish symbiotic environments for optimal collaboration between human and machine. Nevertheless, proposed symbioses are always unidirectional, namely pursuing the benefit for just the human component. This confines the machine to a purely servant role: they actually co-exist with humans in the same working environment (under more flexible safety constraints, thanks to the advancement of collaborative robotics), but just giving them the required support in very specific and limited situations.

The Mutualism Framework aims at overstepping this concept by proposing that both robots and human operators are treated as intelligent agents (Symbionts), each with its own special traits, exchanging bidirectionally physical support, information and even knowledge of the process. In this new vision, also robots (machines) and, more in general, intelligent devices can be the addressees of support and training actions, with human operators transmitting knowledge and experience to them.

Making the symbiosis mutualistic provides two innovative ways of exploiting the role of machines:

i. human–robot automation tasks can be designed exploiting real collaboration, thanks to the continuous exchange of orchestration signals between symbionts;
ii. intelligent mechatronic systems are transformed into active repositories of manufacturing knowledge.

8.3.3 Three-Dimensional Characterization of Symbionts' Capabilities

Worker characterization is traditionally performed considering just a subset of all the possible describing dimensions: vital statistics, ergonomics and anthropometry; functional capacities; knowledge and experience. In fact, these are rarely included at the same time in the creation of a dynamic worker profile where all these elements holistically concur to a unique profiling strategy.

On the other hand, the ongoing transition towards the concept of Cyber-Physical Systems (CPS) for mechatronics is still incomplete, meaning that we have not yet reached a level of maturity where CPS are treated as intelligent agents that may evolve in time (i.e. machine learning) and, as such, require an equally dynamic characterization strategy.

The Mutualism Framework aims at providing a comprehensive assessment and characterization approach of Symbionts (both humans and robots) operating in its shop floors, to find valuable win–win combinations for effective execution of collaborative tasks.

Under a common overarching interpretation methodology, all the considered and monitored characteristics will be used to define, on a task-wise basis, a three-dimensional picture representing a generic symbiont profile (Figure 8.3) in terms of:

- Experience, which indicates the symbiont level of practice in executing that tasks. A proper taxonomy is thus required to quantify and qualify the level of experience also considering the practice gained using edutainment tools and virtual/augmented reality environments;

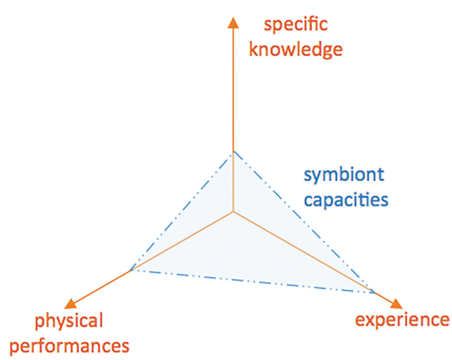

Figure 8.3 Three dimensions of characterization of Symbionts.

- Specific knowledge, related to the level of knowledge to correctly understand and handle a specific subject. It refers to a theoretical or practical understanding of the topic which can be either implicit or explicit;
- Physical performances, to include the quantification of the physical characteristics (such as movement capacities, strength in different positions and operations, sensorial capabilities, etc.) that are needed to execute that task.

8.3.4 Machine Learning Applied to Guarantee Dynamic Adherence of Models to Reality

Kruger et al. [14], in a review study on human–machine cooperation types in manufacturing systems, state that cooperation is an important aspect for flexibility, adaptability and reusability. As also stated by Ferreira et al. [15], manufacturing systems have been pressed in recent years to provide highly adaptable and quickly deployable solutions to deal with unpredictable changes following market trends. But what about the adaptability (short term) and evolution (mid/long term) of the capacities of both human operators and robots? In fact, workers' performances may importantly vary even on a day-by-day basis, while learning-augmented mechatronic systems are conceived to improve over their life cycle.

The Mutualism Framework puts the dynamicity of a Symbiont's characterization as one of its cornerstones, proposing to integrate this sort of "live portrait" into a so-called Virtual Avatar, that is, a digital representation of the Symbiont that implements the characterization data model and is fed of real-time information coming from the shopfloor, where humans and robots operate and interact. Avatars will not be simply passive containers of information concerning symbionts; they will also be able to represent that part of their dynamics (= behaviours) which is needed to design and then run an adequate orchestration towards the common manufacturing goals

8.4 Technological Approach to the Implementation of Mutualism

To transform the aforementioned concepts into a valid implementation of the Mutualism Framework, several technological contributions are needed, integrated in a coherent functional architecture, as represented in Figure 8.4.

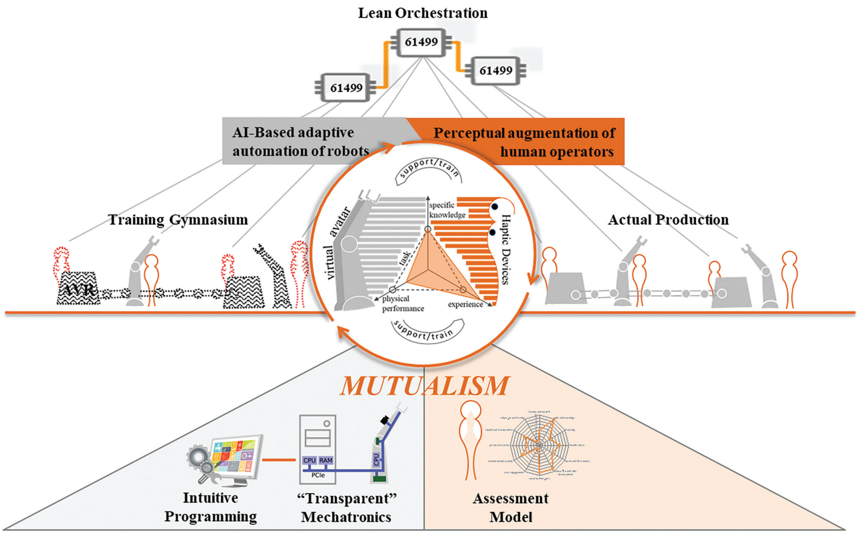

Figure 8.4 Qualitative representation of the technological key enabling concepts of the Mutualism Framework.

8.4.1 "Mutualism Framework" to Sustain Implementation of Symbionts-Enhanced Manufacturing Processes

Mutualistic symbiosis constitutes the fundamental brick to boost worker centrality in real production environments, where human–robot collaboration is put as a cornerstone. For this to become a new design and runtime paradigm, a "Mutualism Framework" must be established, that is, a sound methodological characterization of what the Symbionts are and of how their mutualistic interactions are modelled and exploited.

The Mutualism Framework (MF) explores four major aspects of the above-mentioned functional architecture:

- A dedicated semantic data model to describe all the elements of the Mutualism concept;
- An assessment model to capture the dynamics of their characteristics (slow) and behaviours (fast);
- The functional mapping, on a per-task basis, between the dynamic representation of Symbionts and their 3-dimensional (experience, specific knowledge and physical performances) profile;
- An overarching set of indicators to evaluate the multi-dimensional performance of Symbionts.

Clearly, for what concerns the intelligent mechatronic systems (= robotic symbionts), the assessment model is directly linked to their functional and non-functional specifications. On the other hand, characterization of human symbionts must consider in a holistic approach all its major "dimensions":

i. Vital statistics, ergonomics and anthropometry, filling the existing gaps of the state of the art, especially for what concerns the variability of these aspects due to the physical and non-physical exposure at the collaborative workplace;
ii. Functional capacities, to consider the relation between workers' abilities and the potentially assigned tasks, and to sustain the corresponding AI learning of robots;
iii. Knowledge and expertise, to effectively and systematically enable knowledge sharing and transfer among workers but also between humans and robots.

The second key focus of the Mutualism Framework is about quantification of performance of collaborating human and robots (measured and/or foreseen), on a per-task basis, but under different perspectives. In fact, the 3D profiling previously introduced provides a simplified but effective way of evaluating how much different Symbionts are "fitting" to execute a specific activity, independently from how such level of adequacy is achieved (i.e. differently between operators and machines); this enables the adaptable orchestration of collaboration based on IEC-61499.

Contemporary, performance of the mutualism must be assessed, to define and then evaluate the achievement of specific process objectives. The MF puts worker's safety (Physical AND Psychological) and well-being as cornerstone of its set of KPIs, without forgetting about manufacturing sustainability (economic, environmental and social) and reconfigurability, and compliance with regulations in force.

8.4.2 IEC-61499 Engineering Tool-Chain for the Design and Deployment of Real-Time Orchestrated Symbionts

During the ongoing transition towards Industry 4.0, the concept of highly distributed intelligent mechatronic devices (also called CPS) is emerging, whose joint behaviour satisfies the production objectives, while guaranteeing much higher flexibility and reconfigurability. This convergence of the industrial world towards an agent-based paradigm for industrial automation asks for adequate new methodologies and technologies for the so-called (real-time) Orchestration of these distributed systems and, thanks to the support of

Daedalus, the open and interoperable IEC-61499 standard is taking the lead in solving this need.

With the Mutualism approach, it is recognized that a collaborating team of human and robotic symbionts is, in fact, an extension of the above-mentioned concept of distributed intelligence, to encompass the hybrid nature of shopfloors where operators and machines work shoulder-to-shoulder. This means that the concept of Mutualism must be developed towards its technical dimension of (soft) real-time orchestration of Symbionts, designed, deployed and then executed at runtime thanks to the usage of an IEC-61499-based engineering tool-chain.

The design stage of a Mutualistic manufacturing process will consider both the conceptual definition of the specifications of the process itself, and the engineering of the automation logics (through the IEC-61499 formalism and programming language) that will control orchestration of the distributed intelligence of Symbionts.

Conception of the Mutualism is where the principles of Lean Manufacturing are applied towards a new production model that considers the opportunities of human–robot collaboration and therefore exploits them. It originates from the key principles of the "Toyota Way" (especially the kaizen) to implement Mutualism keeping the Human operator at the centre of the process.

Leveraging on the state of the art of R&D on "Lean Automation", it is possible to focus mostly on the implementation of those design-support tools that can simplify the definition of requirements for Mutualistic tasks, help assembling the most appropriate team of Symbionts for those tasks and support the generation of specifications for the corresponding IEC-61499 orchestration.

For what concerns the engineering of orchestration logics, the usage of the IEC-61499 IDE and runtime developed in Daedalus allows to: (i) Guarantee ease of interfacing and functional wrapping of lower-level automation architecture of specific robotic symbionts; (ii) Use 61499 formalism to consider the 3D performance of Symbionts and (iii) Integrate with an adequate perceptual learning platform.

8.4.3 AI-Based Semantic Planning and Scheduling of Orchestrated Symbionts' Tasks

Complementary to the IEC61499-based design stage of Mutualism is the development of the Mutualism Execution Platform (MEP), that is, a set of

IEC-61499-Compliant runtime modules to adapt continuously the orchestration of human and robotics symbionts. In fact, the management of the runtime stage of the orchestration of distributed symbionts is where the flexibility and adaptability enabled by the mutualistic symbiosis of humans and robots is achieved effectively.

The collaboration between operators and machines designed within the IEC-61499 IDE is then operatively achieved by the MEP, deployed within the shopfloor and connected in real time to both machines and workers through the IEC-61499 runtime framework. In fact, it is responsible for defining the most suitable optimization pattern(s) to be executed over a specific time horizon and adapting coherently with the variability of production and workers' needs.

In practice, the MEP can exploit availability of ready-to-use AI-based techniques to tackle the operational challenges of robust planning and scheduling (over a distributed agents' functional architecture) the team of Symbionts needed to reach specific production objectives, considering that:

- First, P/S human activities are complex by itself, since people have different skills, attitudes and preferences; moreover, working shifts and rosters are subject to strict union and legislative regulations that cannot be violated, but force severe restrictions on working plan feasibility.
- Second, although machines do not have "personal" preferences and they are not subject to "union" regulations, they must undergo precise and rigorous maintenance plans, which must ensure that the operating conditions of each machine meet very high operating standards and security rules.
- Third, humans and machines are called to cooperate in a highly dynamic and uncertain environment where the tasks to be executed constantly evolve and their distribution (over different symbionts) and scheduling must be very robust.

The second key aspects of dealing with the runtime management of Mutualism is to provide intuitive programming tools, which enable advanced users and shopfloor workers to program novel robot skills that are verifiably compliant with IEC-61499. This requires the analysis of robotic skills with linear time temporal logic model checking. These programming tools can be based, for instance, on RAFCON [16], a visual programming tool for robotics skills that enables logging with semantic labels, so that the context in which data was logged is known. Having contextual knowledge greatly facilitates the data-driven analysis of skills [17], and the application of data mining techniques.

8.4.4 Modular Platform for Perceptual Learning and Augmentation of Human Symbionts

Intelligent mechatronic systems exchange (potentially strict real time) I/O signals to sustain high-performance interactions. Humans do not; in fact, despite having an incredibly sophisticated and flexible set of sensing and actuating apparatus, their capacity of receiving and transmitting complex and structured information is very limited. This (very simply introduced) specific issue is also one of the major reasons for which, until now, human–robot collaboration has been severely hindered: orchestrating physical tasks accomplished by distributed agents requires a bi-directional information flow continuously exchanged WHILE those tasks are being executed.

This aspect of the Mutualism is tackled from a systemic point of view, aware of the fact that what is needed today is not so much a new, very specific smart sensing or interfacing solution (those are already developed and released continuously at market level) as rather a HW/SW abstraction layer to:

i. Simplify the aggregation and elaboration of several and heterogeneous signals coming from and going into the shopfloor (through multiple devices) and
ii. Provide already integrated interpretation and machine learning functionalities, then available to the orchestration layer for increased flexibility and adaptability.

Following the natural distinction induced by the bi-directionality of signals to be exchanged between human and robotic Symbionts, it is correspondingly possible to identify two major contributions: holistic monitoring and learning of Virtual Avatars, and adaptive cognitive interfacing.

The first component is a hierarchical functional architecture composed of three layers: A modular monitoring system composed of distributed smart sensors; a data-interpretation layer and a machine learning middleware to provide high-level tasks. To assure an adaptive manufacturing environment, data gathering for worker profile adaptation will be continuous, performed both during everyday manufacturing operations and within properly designed training sessions.

Complementary to this is the possibility of sending feedback to an operator, directly from a robot, to enable the coordination of their respective activities during the execution of joint tasks (which may involve also several symbionts). We call this an adaptive cognitive interfacing, achieved through the augmentation of the capabilities of the worker through dedicated smart devices. Augmented/Mixed/Virtual Reality will be the most important approach to tackle this challenge, knowing that the area of human–robot collaboration is still developing and novel interfaces supporting in an effective way the collaboration need to be designed, implemented and evaluated.

8.4.5 Training Gymnasium for Progressive Adaptation and Performance Improvement of Symbionts' Mutualistic Behaviours

All biological symbioses go through a preliminary training phase, where symbionts know each other and measure up. This step is fundamental also for Mutualism. In fact, improper human–robot interaction may cause counter-effects, such as misuse of machine and/or safety issues.

Because the trust of human to robots will directly affect the degree of autonomy of the industrial robot, which is related to the efficiency of manufacturing processes, trust is a critical element in HRI when a human worker observes a discrepancy between his/her performance and what he/she expects from the robot partner, his/her trust to the robot decreases accordingly. When the robot performance matches human expectation, the human's trust to robot increases.

The solution to this is the so-called Training Gymnasium, where:

- A task recording & displaying facility will enable the recording and retrieval of working parameters, machines movements, machine and worker roles, etc. According to worker literacy rate, the training facility may record or retrieve the above-mentioned parameters;
- Virtual reality environments and devices will be implemented thanks to the augmentation platform. These solutions are especially intended for machines still under design to assure rich workers' experience and value-adding data gathering since the design of new workplaces (with a closed loop with the other phases of the life cycle of the manufacturing process);
- Augmented reality will be used to guide the less skilled workers in interacting with robotics Symbionts and other physical machines.

8.5 The Potential to Improve Productivity and the Impact this Could Have on European Manufacturing

According to Holdren [18], manufacturing has a larger multiplier effect than any other major economic activity: every euro spent in manufacturing drives an additional €1.35. EC data show that in 2012 the manufacturing sector in the EU employed 30 million persons directly and provided twice as many jobs indirectly, manufactured goods amount to more than 80% of total EU exports and manufacturing accounted for 80% of private Research & Development expenditure. This notwithstanding, for diverse and widely discussed reasons, EU manufacturing has slightly declined in the last few years.

European Commission made huge investments in manufacturing topics to reverse this trend, and Advanced Manufacturing has been identified as the major driving force for improving competitiveness of the European Industry, namely through [19] ICT-enabled intelligent manufacturing, more sustainable technologies and processes, and high-performance production. To guarantee flexibility and even total flexibility [20], the European industry needs to adopt new paradigms of production models, focusing on human–machine collaboration, more than what is currently done in fully automatized islands, where humans are out of the decision loop [21], to take benefit of workers abilities, fostering human skills and human motivation [22].

It is therefore necessary to move to a new concept of human-centred automation [23], and it is under this conceptual framework that the Mutualism Framework seeks for an effective symbiosis between human and robots, to overcome the challenges that the European manufacturing industry must face in the years to come:

- To promote value-adding non-repetitive non-alienating jobs in the manufacturing industry;
- Claiming for R&D investments in a wide plethora of knowledge fields;
- Making economically sustainable high-quality production processes that targets overall sustainability;
- Supporting lifelong learning in the shopfloor exploiting AVR;
- Promoting re-shoring of sustainable businesses.

This is clearly aligned with the Europe 2020 policy framework targets for Smart, Sustainable and Inclusive Growth, towards its five major objectives of Employment (75% of the 20–64 year olds to be employed), R&D (3% of the EU's GDP to be invested in R&D), climate change and energy sustainability (greenhouse gas emissions 20% lower than that in 1990; 20% of energy from renewables; 20% increase in energy efficiency), education (reducing the rates of early school leaving below 10%; at least 40% of 30–34 year olds completing third-level education) and fighting poverty and social exclusion (at least 20 million fewer people in or at risk of poverty and social exclusion).

As for different application domains, manufacturing is facing a bend where traditional production processes and work methods must evolve to be more flexible and adaptive to a quick changing context. Many manufacturing companies experience unpredictable and dynamic production environment due to increased customization in their production, low product life cycles and increased competition from low labour countries. To remain competitive in such globalized market, they must adapt their production systems accordingly and create flexible automatic solutions.

Adaptability in manufacturing can be defined as the ability of the production system to alter itself efficiently to changed production requirements. According to Järvenpää [24], manufacturing system adaptability can be achieved either statically (i.e.: while the system is not operating) or dynamically (while the system is running) and working on: (a) physical adaptation (of layout, machines and machine elements); (b) logical adaptation (re-routing, re-planning, re-scheduling and re-programming) and (c) parametric adaptation (changing machine settings).

To fulfil these requirements, reconfigurable manufacturing systems have been proposed as a set of possible solutions, “designed at the outset for rapid change in structure, as well as in hardware and software components, to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or regulatory requirements” [25]. In these systems, human operators remain an invaluable resource, by being superior to robots at rapidly interpreting unplanned tasks and situations and handling flexibility and complexity.

Six core properties of reconfigurable manufacturing systems impact the overall time and cost of reconfiguration and for each of them the Mutualistic Framework based on IEC-61499 is capable of providing a concrete technological and methodological answer:

- **Scalability** (design for capacity changes): The dynamic creation of Mutualistic teams, thanks to the IEC-61499 orchestration layer, allows to manage rapid changes of production capacity by simply adding or removing new symbionts from the shopfloor event at runtime stage. Two major technological innovations guarantee this level of reconfigurability: (i) The IEC-61499 platform support to plug & produce, integrating functionalities of auto-discovery and auto-configuration of symbionts; (ii) The dynamic planning and scheduling of mutualistic tasks, looking for the best coupling of characteristics and skills of Symbionts, which guarantees to exploit the introduction (or removal) of one member of the team in the most appropriate way.

- **Convertibility** (design for functionality changes): the Mutualism Framework brings ease of programmability directly at the hands of human operators, thanks to its dedicated intuitive interfaces. To achieve a greater flexibility along with a more efficient production, traditional industrial robots are substituted by flexible and autonomous robotic systems with an intuitive on-the-fly programming, enabling an ideal batch size of 1. This translates into a faster and less costly management of the re-conversion of functionalities of robotic symbionts, even over the very short term. This aspect is further enhanced by machine learning capabilities of robots, which enables a direct adaptation (without programming actions) of the behaviour with respect to minor changes of requested functionalities.
- **Diagnosability** (design for easy diagnostics): An effect of the human–robot symbiosis is that the monitoring and inspection capabilities of robots can be directly used by human operators to augment their perception of the working environment and of the production process. Thanks to an appropriate AVR layer, it is possible to provide to human Symbionts contextual and dynamic information, leading to much better error diagnosis.
- **Customization** (flexibility limited to part family): This is one of the drivers most impacted by a more extensive usage of HRC, since it is where manufacturing activities are currently done mostly by human operators. Through its IEC-61499-based approach to orchestration, the framework guarantees a new degree of collaboration in executing joint tasks, especially those which require variations within the same part family. The flexible implementation of the automation logics for these mutualistic tasks considers, from design stage, how they will be executed by hybrid human–robot teams, where single behaviours will be dynamically adapted. This means that operators will be able to exploit their natural cognitive flexibility to modify the activity with respect to the single part, while robots will consequently adapt to this human-induced changed.
- **Modularity** (modular components): the whole concept of Symbionts is targeted towards an extreme modularization of functional units but guaranteeing their ease of interchange through an elevated degree of decentralized intelligence. While this is natural for human operators, the innovation of the Mutualistic Framework is to bring the same approach to robots and to then bring physical and functional modularity into a dynamic integration with the unique IEC-61499 orchestration layer.

This means proposing a systematic way to design its orchestration in a robustly reconfigurable way.

- **Integrability** (interfaces for rapid integration): this key driver of reconfigurability is where the interoperable and open nature of IEC-61499 maximizes its impact. The approach of proposing this integration and orchestration layer is a major enabler to implement real plug & produce functionalities for the intelligent symbionts of Mutualism. The 61499 platform acts both as abstraction layer with respect to the lower levels of automation and, at runtime stage, as manager of the dynamic integrability of new Symbionts into a specific mutualistic task.

8.6 Conclusions

During the coming decades, the whole European manufacturing sector will have to face important social challenges. In fact, while shop floor operators are usually considered a "special" community, with their job being considered one of the most disadvantaged in terms of workplace healthiness and safety [26], Europe's issue of an ageing population will lead inevitable workers to postpone their retirement age. With this prospect, without a concrete solution, the European industry is condemned to lose qualified workers who are needed for manufacturing high-quality products, while national assistance frameworks of EU-27 will have to assist retired workers who need to be kept active to balance the new demographic distribution of population.

Through the Mutualism Framework based on the IEC-61499 platform of Daedalus, we answer back to the popular belief that automation wipes out many jobs and that is currently under the attack of many Industry 4.0 opposers. Indeed, recently, several experts have repeatedly proven this thesis as groundless, demonstrating the mutually virtuous coexistence of humans and machines interacting in industrial environments [27]. Even in advanced automated scenarios, where machine learning can support adaptation to variable and unpredictable situations, interaction with humans is still essential in the process of reacting to contextual information (thus, machines need workers). Contemporarily, automation encompasses not only repetitive tasks, but also sophisticated and high-performance functionalities that human's senses and capacities are not keen to; moreover, machines could compensate human knowledge gaps, thus extending the opportunity to have actual support for junior workers (thus, workers can benefit from machines).

The deployment of these technologies may improve the mental and physical strain on human operators, reducing the number of injuries related to manufacturing work. In the medium term, this will also improve the perception of shopfloor workers about how their job negatively influences their health status (currently 40% [28]). This will be mirrored within the society, improving the general perception that population has about shopfloors and increasing social acceptance of this profession.

At the same time, the opportunity is to bring new skills to the role of the shopfloor worker, increasing the reputation of operators at social level. The new task typology that operators will have to perform will create jobs opportunities at shop floor level for more qualified profiles like technicians, increasing appealing for younger workers. This is in line with current FOF Roadmap 2020 to achieve sustainable and social acceptance of this sector and to strengthen the global position of the EU manufacturing Industry.

Finally, the implementation of Mutualism distributes dynamically tasks between operators and robots and coordinates their collaborative execution according to their strengths and weaknesses. This approach offers new job opportunities to people with disabilities, as the automation can overcome functional limitations, facilitating inclusion of this community.

Acknowledgements

The work hereby described was achieved within the EU-H2020 project DAEDALUS, which was funded by the European Union's Horizon 2020 research and innovation programme, under grant agreement No. 723248.

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