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A framework to design a human-centred adaptive manufacturing system for aging workers



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ABSTRACT

The so-called smart manufacturing systems (SMS) combine smart manufacturing technologies, cyber-physical infrastructures, and data control to realize predictive and adaptive behaviours. In this context, industrial research focused mainly on improving the manufacturing system performance, almost neglecting human factors (HF) and their relation to the production systems. However, in order to create an effective smart factory context, human performance should be included to drive smart system adaptation in efficient and effective way, also by exploiting the linkages between tangible and intangible entities offered by Industry 4.0. Furthermore, modern companies are facing another interesting trend: aging workers. The age of workers is generally growing up and, consequently, the percentage of working 45–64 years old population with different needs, capabilities, and reactions, is increasing. This research focuses on the design of human-centred adaptive manufacturing systems (AMS) for the modern companies, where aging workers are more and more common. In particular, it defines a methodology to design AMS able to adapt to the aging workers' needs considering their reduced workability, due to both physical and cognitive functional decrease, with the final aim to improve the human-machine interaction and the workers' wellbeing. The paper finally presents an industrial case study focusing on the woodworking sector, where an existing machine has been re-designed to define a new human-centred AMS. The new machine has been engineered and prototyped by adopting cyber-physical systems (CPS) and pervasive technologies to smartly adapt the machine behaviour to the working conditions and the specific workers' skills, tasks, and cognitive-physical abilities, with the final aim to support aging workers. The achieved benefits were expressed in terms of system usability, focusing on human-interaction quality.

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1. Introduction

In the context of Industry 4.0, manufacturing has to be smart and adaptive thanks to collaborative and flexible systems able to autonomously solve the problems arising during the process [26]. For this purpose, increasing attention has been recently paid to pervasive and smart decision support systems able to optimize machines' features and behaviours according to collected data, current conditions and process requirements. To face this highly complex scenario, the Industry 4.0 initiative has been launched in Germany and is actually strongly promoted by the European strategic programs due to its potential to change the European economy via cyber-physical systems (CPS) [27]. In this scenario, major approaches for increasing production changeability and flexible control are based on reconfigurable systems able to cope with

unpredictable situations and dynamic production scenarios [30]. Cyber-physical systems (CPS) can be used to bring machine autonomous control, have self-adaptive behaviours and intelligently react to specific conditions. Current smart manufacturing implementations are mostly at the plant and production level, and use information technology, sensor networks, computerized controls, and production management software to improve process efficiency as a key performance objective [46]. However, such adaptivity is oriented so far to mostly optimize the production system efficiency in term of time, costs and production rates, while human factors (HF) have not been included in such scenario. It means that even in smart factories human beings (i.e., workers, operators, technicians) has to operate in a new manner, with the support of enhanced information sources available in modern industries.

The attention to human factors in industry is an emerging trend, and represents a relevant topic also for advanced engineering informatics applications. Starting from the extraction of human-based knowledge to create intelligent computer integrated manufacturing systems [63], to the analysis of both physical ergonomics

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and human cognition to develop smart production environments [59,60].

Today, the Industry 4.0 framework has the potential to include also humans into its highly innovative processes, and in particular aging workers that have specific needs and abilities. This is a crucial aspect for modern companies since the demographic changes as well as national regulations for late retirement, and a greater health that allow people to work for a longer period, are responsible for a sensible increase of the workers' age [33]. In this context, adaptive manufacturing systems (AMS) can successfully be a part of modern production systems to support workers in everyday jobs thanks to adaptive behaviours according to the occurring events as well as the human actions and capabilities.

Human-centred design is becoming crucial in manufacturing system design due to two main factors: the increasing age of workers as a consequence of global population aging, and the growing complexity of systems that are hard to manage and maintain. Indeed, it is widely recognized that the average age of world population is growing, as a global and continuous trend, affecting humans in general and thus also people working in manufacturing contexts [48]. Numerous studies claim that in 2050 around half of workers will be aged over 50 in developed countries, and the presence of older workers in production and operative roles will have an impact on economic growth and manufacturing efficiency [1,17]. As far as the impact of such a trend on companies, studies about aging workers demonstrated that the functional capacities, mainly physical, show a declining trend after the age of 30 years, and the trend can become critical after the next 15–20 years, so that from 45 to 64 years old there is a significant decrease of their capacities, both physical and cognitive ones. Such loss is about 20–25% in respect to the full capacity considered at 30 year old, and it affect both workers involved in physically demanding jobs and mentally demanding positions. Therefore, the age of 45–50 years have often been used as the base criterion to refer to “aging worker” [32]. The “early” definition of aging among workers from the occupational health point of view is due to possibilities for preventive measures: preserving their health and wellbeing is fundamental to maintain their ability longer and better. This is particularly important in the actual era characterized by a participation rate of workers who are aged 45–50 years or older in modern companies processes. Contemporarily, machines are becoming more and more digitalized and technologically advanced, thus they require to workers higher mental abilities, which inevitably decrease with age [42]. In this context, considering HF in system design is fundamental to properly handle with system complexity and make also complex system easy to control, manage and maintain. Problems referred to aging workers (45–64 years old), most of which related to consequences of the aging process as well as to changes in the working conditions and methods, and new demands on workers (e.g., higher flexibility, extended knowledge, polyvalence) have been documented on industrial cases in Europe [62]. In the Industry 4.0 framework, a lot of information can be available to properly manage the human-machine interaction by properly controlling the adaptive behaviours of both machines and interfaces, supporting the above-mentioned problems referred to aging workers. For these purposes, having systematic approaches to bring intelligence into the shop floor is required to provide factories with flexible and adaptive behaviours able to effectively face different working conditions and avoid downtime, delays and production rate decrease. In this context, the present research proposes an approach to design a human-centred AMS based on the flexible adaptation of the machine and interface according to the workers' needs and capabilities. The paper presents the human-centred design approach adopted to correlate workers' needs and system features at different levels (considering the users, the context, the machine, and the interface) and to test the designed

adaptability on virtual prototypes. For this purpose, in particular, it is based on virtual commissioning (VC) approach to model and simulate the smart system and define the most proper adaptive behaviours, and implements case-based reasoning (CBR) algorithms to realize the human-centred adaptive behaviours according to the working conditions, process data, and workers' tasks as well as physical and cognitive abilities. System variables, related to the process, the machines and the workers, are monitored by AMS sensors and connected to the simulated system (i.e., virtual prototype) as well as the control system by CPS. The system is context-aware and is able to change its behaviour according to the defined adaptive rules. As a result, both machines and interfaces can adapt their behaviour according to the process parameters, monitored in real time, as well as to the requirements of the specific user interacting with the system. The industrial case study focused on the re-design an existing machine tool by adopting the proposed approach. Firstly, the human-related problems were analysed and a set of control system parameters were identified. Then, the machine was equipped with sensors and feedback devices to monitor the most critical tasks, and a virtual simulation system has been created to simulate the real process and to define possible adaptive behaviours of the system, by testing also the effect on virtual prototypes. Finally, a system prototype has been developed and tested with users to prove the improved human performance by experimental usability testing, thanks to the new AMS.

Section 2 presents the research background and motivation; Section 3 describes the research approach; Section 4 presents the industrial case study; Section 5 contains concluding remarks and future works.

2. Research background

2.1. Collaborative and smart manufacturing systems

Modern industrial systems are asked to adapt to constantly changing market requirements by maintaining the global competitiveness of manufacturing companies [29]. In this context, smart manufacturing systems (SMS) focus on the integration of interconnected systems into manufacturing industry thanks to the creation of linkages between tangible product-process assets (called also “physics-ends”) and cyber-decision support assets (called also “cyber-ends”) in production, logistics and services, with the final scope is to provide self-aware and self-adapting systems able to intelligently adjust the production patterns [13]. Physics-ends are, for instance, machines, materials, tools, while cyber-ends are data collection and storage tools, data processing systems, monitoring devices, and any other items that create a digital “twin” on the physics items [3]. Among SMS, the so-called reconfigurable manufacturing systems (RMS) and flexible manufacturing systems (FMS) can be included. Indeed, both of them exploit the linkages between their real assets and the virtual ones (emulated) to predict the system behaviour and to adapt its actions and reactions in a flexible way. The main differences between FMS and RMS refer to the systems' flexibility and scalability concerning the production capacity; in particular, FMS refer to a generic system flexibility [9], while RMS usually address on-demand customized flexibility through scalability to incrementally realize different functionalities and capacities [16]. The concept of SMS is more recent but, in a certain sense, includes the previous ones. It refers to a fully integrated, collaborative manufacturing system that responds in real time to meet changing demands and conditions in the factory, in the supply network, and in customer needs, thanks to the new smart technologies and information and communication systems [46]. With respect to RMS and FMS, a SMS is characterized by

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