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Relieving operators' workload: Towards affective robotics in industrial scenarios

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ABSTRACT

This paper proposes a novel approach based on affective robotics that can be applied to industrial applications. Considering a human-robot interaction task, we propose to analyze the mental workload of the operator, and subsequently adapt the behavior of the robotic system, introducing assistive technologies. These technologies would prevent the performances deterioration caused by the human stress, helping him/her only when needed and decreasing the user's mental workload. This represents a general methodology, which can be applied to several industrial applications, leading to increase the overall performances of human-robot interaction exploiting principles of human-centered design. As a case study, we consider a teleoperation task, where virtual fixtures are utilized as an assistive technology. The stress of the operator is monitored in terms of heart rate variability, measured by means of a wearable sensor tied at the operator's wrist. Experimental validation of the proposed architecture is performed on a group of 15 users that teleoperate an industrial robot for performing a pick and place task.

1. Introduction

In the recent years, robots are becoming key elements to achieve manufacturing competitiveness, especially if they are able to collaborate with humans in a shared workspace, creating a co-working partnership. To this end, the initial paradigm for robot usage has changed during the years from an idea in which robots work with complete autonomy in a separate cell, to a scenario in which robots and humans can work together and interact.

Human-Robot Interaction (HRI) is a growing research area: main researches focus on construction, healthcare and assistive robotics, aerospace, edutainment and entertainment, home service, military and industrial applications [1,2]. Robots can help humans in relieving physical effort tasks, carrying heavy loads and conducting repetitive tasks: in [3] authors describe a human-robot dialogue system that allows a human to collaborate with a robot during an assembly task; in [4] authors present a mobile construction robot that performs accurate and delicate building tasks with a new real time framework of "sense and act"; in [5] authors propose a mobile robot that can handle an object in cooperation with a human, sharing the load. With respect to healthcare and assistive robots, applications of HRI have been proposed for assistance for blind people [6,7], social interaction for autistic children [8], elderly care [9,10] and intelligent and autonomous wheelchairs [11,12]. In the space field, robots are used for the exploration of planets [13] and construction of space stations [14]. Another field where robots support and take over for humans is urban search and rescue [15,16]: they can more easily explore and move in collapsed buildings thanks to their small dimensions [17], looking for human victims, in combination with aerial robots to monitor areas from above, after natural disasters [18]. Edutainment and entertainment robots have been employed as tour guides in museums [19], dance partners [20], robotic pets [21] and story tellers [22]. Moreover, for home service, robots are used as vacuum cleaners, home security and household devices [23]. In military field, robots are used as soldiers in remote operations or dangerous ones like bomb disposal [24]. Cooperation with robots is also useful in small-scale tasks, as microassembly and microsurgery, where a high precision is required [25].

As regards industrial applications, in the last years the increasing need for collaborative robotic solutions has been mainly driven from the automotive and electronics industry [26]. Most of the applications in the automotive domain refer to assembly processes, where robots are in charge of those tasks requiring high precision or causing workers repetitive strain injury when done by hand, such as carrying heavy objects [27]. Just to cite few examples, in [28] robots assist humans on physi-

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cally demanding operations like door removal or seat loading, or they can load and transport heavy wheels in tire workshops [29]. Another interesting application field is the oil and gas industry: in [30], HRI is exploited to remotely control a mobile robot for inspection of plants and repairing tasks. Further industrial applications of human-robot collaboration and interaction refer to handling and welding tasks and in [31] the case of assembly of biomedical products is considered. A detailed review on human-robot collaboration in industrial settings can be found in [32].

It is worthwhile noting that the use of collaborative robots in industrial working environment enjoys two major advantages. First, human workers and robots share their complementing skills, such as robots precision, accuracy and repeatability, which are impossible to achieve by humans, and humans innate flexibility and ability to adapt to unforeseen events. Second, using collaborative robots allows to relieve human workers of tiring and physically demanding tasks, which are delegated to robots. However, the introduction of such robotic systems in industrial applications poses also two major issues, which cannot be ignored. Specifically, issues related to safety must be considered, since any harm to the human worker due to proximal interaction with the robot must be prevented. In this regard, a large body of the literature has been devoted to this topic and several technical and governmental regulations have been issued, as recalled in [32]. Additionally, issues related to human factors and cognitive workload for the user have to be considered. Indeed, shopfloor workers, who typically are neither expert nor confident with the use of robots, are requested to work close to such complex systems: this generates anxiety and fear. In particular, an increased operators mental strain in collaborative robotic assembly tasks was reported in [33]. Moreover, in most cases, the introduction of robots changes the way workers are used to perform a task, thus requiring that workers adapt to the new workflow and learn again the task from scratch. These thoughts add to the fact that, in typical industrial work tasks, shopfloor workers have often to accomplish repetitive jobs, or they work in adverse conditions, either environmental, such as noisy places, dangerous environments, dark views, or psychological, due for example to tight time constraints, presence of supervisors and electronic monitoring of job performance [34,35]. Ultimately, in [36] it was proven that there is an association between work stress for industrial employees and the risk of death from cardiovascular disease. Thus, human factors, meant as mental stress induced by close and prolonged interaction with the robot, have to be taken into account when considering and designing robotic industrial applications.

A promising way to achieve this is tuning the interaction with the robot depending on the worker's skills and her/his instantaneous stamina. Indeed, while the former can be considered as constant during the interaction session, stamina varies depending on situational conditions, such as stress, fatigue and specific working environment and tasks. In order to adapt HRI task according to the worker's stamina, an approach based on affective robotics can be exploited. Specifically, affective robotics consists in enhancing the interaction of a human with a robot by recognizing her/his affect [37]. By supervising non verbal communication towards the robotic system during the interaction, such as emotions and feelings, an implicit feedback can be obtained. This implies that, when worker's stamina is increased, human weakness can be detected and the robot can adapt its behavior and compensate the human temporary lack, reducing the user's cognitive load. Affective robotics has been mostly used in the context of social robots [37], where an interpersonal human-robot communication is desired. For example, in [38] affective robotics is exploited to reach a smooth and natural HRI, considering a model of affect that gathers emotions, moods, and attitudes, particularly with regard to long-term responses. Few works exist with respect to service robots. In [39], authors develop a Hidden Markov Model to estimate the human affective state in real time, using robot motions as inducements, to obtain a more natural HRI. Moreover, in [40] an approach to HRI is presented that allows users to intuitively interact with a robot and takes into account mental fatigue, providing adequate support when necessary. The idea of implementing affective computing for interacting with automatic machines has been considered in the European project INCLUSIVE, which has recently started [41]. However, to the best of the authors' knowledge, no attempts have been considered yet on integrating affective robotics in industrial applications, where situational constraints (such as stress and psychological pressure) make the interaction more critical and tend to reduce human operator's acceptance of robotic systems.

Rather than adapting the interaction to the current psychophysiological condition of the worker, classical approaches used in industrial practice resort to user profiling, that is off-line measuring the skills and capabilities of the user and adapting the user interface accordingly (see, e.g., [42] and references therein). Off-line profiles can be built upon analysis of worker's skills (like experience, knowledge, training, competence and education), information processing ability and cognitive and physical impairments. However, this approach does not take into account the online evolution of the user's aptitude and her/his mental workload. Furthermore, it is worthwhile noting that workers' physical fatigue is considered in [43] and it is explicitly taken into account in the design of a collaborative robotic cell for manufacturing tasks. In particular, tasks are assigned either to the robot or the human operator depending on the level of his/her physical fatigue.

Recently, support tools based on augmented or virtual reality have been proposed to assist workers and guide them in the interaction with robotic systems. Both of these approaches result into augmenting natural feedback to the operator with simulated cues [44]: with augmented reality, the user maintains a sense of presence in the real world and only virtual elements are added; with virtual reality, the user is totally immersed in a virtual environment and her/his senses are under the control of the system. Specifically, several solutions have been proposed aiming at assisting workers in tasks related to planning [45], maintenance [46] assembly design [47], where the optimal operation sequence that minimizes completion time and effort must be found. However, neither these methods make any distinction between different cognitive capabilities of the users or their experience and sensitivity toward the system.

1.1. Contribution and organization of the paper

To overcome the above mentioned limitations, we propose to combine industrial and affective robotics to design an anthropocentric industrial robotic system, whose behavior changes according to the worker's feelings and reactions, becoming flexible towards different typologies of users and tasks. On the one side, the proposed approach is intended to relieve the user's mental workload when the interaction with the robot becomes not sustainable for the worker. On the other side, we ultimately aim at making industrial robots accessible also to inexpert users, who do not feel confident or do not have experience of interactive tasks, and thus are excluded when creating employments in this field.

Generally speaking, affective robotics is based on real-time measurements of physiological parameters that are indicators for mental strain, such as blood volume pulse and heart rate variability, electrodermal activity, body temperature, electroencephalography, hormonal balance and the analysis of oculomotric functions or speech. Specifically, we propose to monitor worker's mental strain from the analysis of heart rate variability, which is a reliable marker of cognitive stress, as detailed in the next section. Moreover, monitoring operator's cognitive workload in working environments requires the use of unobtrusive tools, which do not limit her/his freedom of motion and not interfere with the task to accomplish. To this end, we propose to measure heart activity, and hence heart rate variability, by using a commercial smartwatch, which embeds a heart rate sensor.

The system, starting from a nominal common condition (i.e., without any change from the original task), monitors the worker's stamina and, when a stressful situation is detected, adapts itself, by simplifying the execution of the task. Examples of task simplification in response to