Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications

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A B S T R A C T
Easy-to-use collaborative robotics solutions, where human workers and robots share their skills, are entering the market, thus becoming the new frontier in industrial robotics. They allow to combine the advantages of robots, which enjoy high levels of accuracy, speed and repeatability, with the flexibility and cognitive skills of human workers. However, to achieve an efficient human–robot collaboration, several challenges need to be tackled. First, a safe interaction must be guaranteed to prevent harming humans having a direct contact with the moving robot. Additionally, to take full advantage of human skills, it is important that intuitive user interfaces are properly designed, so that human operators can easily program and interact with the robot. In this survey paper, an extensive review on human–robot collaboration in industrial environment is provided, with specific focus on issues related to physical and cognitive interaction. The commercially available solutions are also presented and the main industrial applications where collaborative robotic is advantageous are discussed, highlighting how collaborative solutions are intended to improve the efficiency of the system and which the open issue are.

1. Introduction
Much of the effort to design and develop today’s safe, human friendly and adaptable robots come from manufacturers of industrial robots. Robots play a pivotal role for today’s manufacturing industry to be competitive. The last estimates by International Federation of Robotics report that until 2019 the worldwide annual supply of industrial robots will increase, on average, of 13% per year, with a final estimate of 2.6 million industrial robots in operation worldwide in 2019 [1]. Despite an increasing need of robots in all industrial sectors has been found in recent years, the strongest demand pertains to the automotive industry, followed by the electronics one, which has been experiencing an increasing high volume order since 2013 [1]. Moreover, it has been found that small and medium sized companies are increasingly using industrial robots thanks to the availability of affordable solutions and compact and easy-to-use collaborative robots [1]. Hence, collaborative solutions, where human workers and robots share their skills, are entering the market and becoming the new frontier in industrial robotics [1,2]. The use of collaborative robotic solutions is also supported by the current trend of automation and data exchange in manufacturing technologies, the so called Industry 4.0 [3]. Ultimately, Industry 4.0 aims at achieving efficiency, cost reduction and productivity increases through integrated automation. In this novel scenario, future production systems will be characterized by individualized products under the conditions of a highly flexible mass production. Thus, new solutions for increased flexibility and interoperability, such as flexible robotic equipment and intelligent decision making software platforms, must be investigated. To this end, robots should be quickly and intuitively operated by humans, while guaranteeing a safe close interaction.

Collaborative robots, also called cobots [4], enable direct interaction between human operators and robots, thus overcoming the classical division of labour, still today prevalent on factory floors, which requires robots to be confined in safety cages far away from human workers. Being possible for the worker and the robot to work alongside each other in collaboration, the worker’s productivity is enhanced, while her/his stress and fatigue are reduced. The greatest advantage brought by collaborative robots lies in the opportunity to combine the advantages of automation with the flexibility and cognitive and soft skills of human workers. Specifically, traditional industrial robots can perform the tasks they are programmed for continuously and with levels of accuracy, speed and repeatability impossible to achieve by humans. However, they lack in versatility and cannot efficiently adapt to dynamic working environments or changes in production, thus being
unsuited for small batches of production. On the contrary, human workers have an innate flexibility and ability to adapt to unforeseen events and maintain strong decision making skills also in dynamic and complex environment.

Additionally, the use of collaborative robots in industrial processes proves beneficial also given the fact that they can be managed and taught through intuitive systems, based on augmented reality [5], walkthrough programming [6,7] or programming by demonstration [8], just to cite few examples. On the contrary, traditional non collaborative robots often need expert specialist engineers to program the robot since, according to traditional programming approaches, instructions to robots have to be explicit and motion oriented, basically specifying a set of points which the robot must pass through.

Further, a paramount limitation of non collaborative robots is related to safety issues. The existing applications separate the human worker from the robot’s working area by means of physical or sensor-based barriers in order for the operators’ safety to be ensured, as shown in Fig. 1(a). Such barriers are eliminated when collaborative robots are used since they host several safety mechanisms that prevent harming humans moving around (Fig. 1(b)). Typically these robots are lightweight and can be easily moved, and embed several sensors to detect and avoid collisions. Table 1 recalls the differences between traditional industrial robots and collaborative robots [9].

In addition to the economic and technical advantages mentioned above, a concrete social impact of human–robot collaboration (HRC) has been reported in terms of a positive net effect on labour demand in Europe [1,2]. Specifically, it is considered that new development in robotics have an impact on the creation of new jobs and opportunities, rather than replacement of workers [2,10]. Accordingly, cobots can act as reliable and accurate co-workers for blue collars.

1.1. Main challenges in HRC

Considered the above motivation to the introduction of collaborative robots in industrial processes, the following main challenges in HRC, which are shown in Fig. 2, can be identified.

First of all, safety issues are the primary main challenge that must be tackled by any approach implementing collaboration between humans and robots. Indeed, being the intrinsic aim of HRC to allow a direct contact between them by eliminating fences, this must be achieved in a safe manner.

Moreover, to take full advantage of human skills, it is important that intuitive user interfaces are properly designed, so that human operators can easily interact with the robot. This requires that, on the one hand,
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