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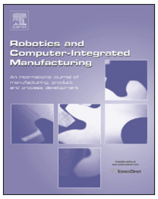

Full length Article

Collaborative manufacturing with physical human–robot interaction

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ABSTRACT

Although the concept of industrial *cobots* dates back to 1999, most present day hybrid human–machine assembly systems are merely weight compensators. Here, we present results on the development of a collaborative human–robot manufacturing cell for homokinetic joint assembly. The robot alternates active and passive behaviours during assembly, to lighten the burden on the operator in the first case, and to comply to his/her needs in the latter. Our approach can successfully manage direct physical contact between robot and human, and between robot and environment. Furthermore, it can be applied to standard position (and not torque) controlled robots, common in the industry. The approach is validated in a series of assembly experiments. The human workload is reduced, diminishing the risk of strain injuries. Besides, a complete risk analysis indicates that the proposed setup is compatible with the safety standards, and could be certified.

1. Introduction

The concept of *cobots*, i.e., robots collaborating with human workers in manufacturing assembly lines, dates back to the pioneer work [1]. In fact, cobots – designed for the assembly line worker – can reduce ergonomic concerns that arise due to on-the-job physical and cognitive loading, while improving safety, quality and productivity. This is a key issue, since according to statistics of the Occupational Safety and Health Department of the US Department of Labour,[1] more than 30% of European manufacturing workers are affected by lower back pain, leading to enormous social and economic costs. A thorough state-of-the-art on human–machine cooperation in manufacturing lines is provided in [2]. At the time of that survey (2009), the only hybrid assembly systems in manufacturing processes were weight compensators/balancers. However, the authors clearly point out the need for more advanced collaboration: although humans remain indispensable in many assembly operations, ergonomic tools assisting their duties are fundamental.

In this paper, we focus on a target application, proposed by PSA (Peugeot Citroën) in the frame of the French National Project ANR ICARO. The application is the assembly of an Rzeppa homokinetic joint, an operation that is currently done manually in the PSA line, causing muscular pain to the workers. In this work, we propose a novel, collaborative human–robot design, of this cell.

The main contributions of this work are outlined below.

- In contrast with most existing human–machine manufacturing applications, where collision avoidance is guaranteed by a minimum security distance [2], our framework successfully manages direct physical contact between robot and human, and between robot and environment.
- In our design, the robot alternates active and passive behaviours during assembly, to lighten the burden on the operator in the first case, and to comply to his/her needs in the latter.
- In contrast with most similar works, our approach can be applied to standard position (and not torque) controlled robots, common in the industry.

From the end user (PSA) viewpoint, two aspects are particularly noteworthy. First, since the operator load is reduced by approximately 60%, the proposed assembly cell can be reclassified in the PSA ergonomics scale. Second, a complete risk analysis by PSA indicates that the proposed setup is compatible with the safety standards, and could be certified.

The article is organized as follows. Section 2 summarizes the state-of-the-art in collaborative manufacturing, and highlights our contributions in the context of current, related research. In Section 3, we present the targeted application: collaborative assembly of a homokinetic joint. The proposed framework is outlined in Section 4. The framework components (nominal trajectory generation, admittance control, and safety monitoring) are then detailed in the

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[1] www.osha.eu.int

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following sections (respectively, Sections 5–7). Experimental results are reported in Section 8, and finally summarized in the Conclusion.

2. Related work

This section summarizes the current state-of-the-art in collaborative manufacturing. We first review the more application-oriented research on human–machine cooperation (Section 2.1), and then the academic research on physical human–robot interaction (Section 2.2).

2.1. Research on human–machine cooperation in the industry

The authors of [3] provide a very rich overview of the emerging technologies in automotive assembly, including the supporting systems (mainly the information technologies). They show that mass customization requires high technological flexibility, and propose various designs to cope with this, by integrating both automated and human-based assembly. A similar perspective is that of the recent EU project ROBO-PARTNER [4], that aims at integrating assembly systems, and human capabilities. The main enablers, according to the authors, are: intuitive interfaces, safe strategies and equipment, proper methods for planning and execution, and the use of mobile robots, and of distributed computing. More recently, the U.S. Consortium for Automotive Research conducted a study on feasibility of fenceless robotic cells for automotive applications [5]. The study defines the levels of human–robot collaboration according to the cell complexity, to drive the probabilities of successful implementation. But as in the previously cited survey [2], the paper exposes the absence of high level human–robot collaboration, apart from “Intelligent Lift Assistants”.

Although some automotive manufacturers are gradually introducing robots in their human production line [6,7], a crucial question persists: how should a collaborative robotic cell be designed? Various researchers have looked into this. Papakostas et al. [8] discuss the key features of cooperating robotic cells in automotive assembly, and provide simulated comparisons of two scenarios: a conventional welding robotic cell, and one with cooperating robots. The authors of [9] assess five alternative safety designs, covering both hardware and control design, of a human–robot collaboration prototype cell for cable harness assembly. In [10], a new cell production assembly system, with human–robot cooperation is developed. The system consists of three key technologies; parts feeding by double manipulators on a mobile base, production process information support for the operator, and safety management for cooperation between operator and robot. The main target of [11] is safety of the shared work cell, in the absence of physical fences between human and robot. Since safety options provided by basic infrared sensors are limited, the authors design a network architecture of these sensors, for tracking user positions, while avoiding collisions. The authors of [12] propose a method for optimizing task distribution among workers and robots. The method is validated, using an ABB Dual Arm Concept Robot, in a PLC Input/Output module assembly scenario.

2.2. Research on physical human–robot collaboration

Recent robotics research focuses on the study and characterization of physical human–robot interaction (pHRI [13,14]). The goal is to enable close collaboration between human and robot, in all service and industrial tasks, that require the adaptability of humans to be merged with the high performance of robots in terms of precision, speed and payload [15]. In this context, it becomes indispensable to define safety and dependability metrics [16–19]. These can contribute to the definition of standards, such as the recent ISO 10218-1:2011 “Safety requirements for industrial robots”.[2]

In this line of research, many solutions for realizing safe collaborative tasks have been explored in recent years. Although these solutions have not yet been transferred to the industry, we hereby list some of the most relevant theoretical works. In [20], a deformation-tracking impedance control strategy is designed to enable robot interaction with environments of unknown geometrical and mechanical properties. For successful interaction with unknown environments and operators, the robot should behave in a human-like manner. This is the target of the research in [21,22]: a human-like learning controller is designed, to minimize motion error and effort, during interaction tasks. Simulations show that this controller is a good model of human–motor adaptation, even in the absence of direct force sensing. A robust controller for a collaborative robot in the automotive industry, is extended in [23], to manage not only the interaction between an industrial robot and a stiff environment, but also human–robot–environment and human–robot–human–environment interactions.

Other researchers have focused more on industrial applications. For example, an industrial robot controller, incorporating compliance of the joints with the environment, is presented in [24]. The desired pose of the tool center point is computed from the force error. Parallel control considers a reference trajectory while allowing feedforward in force controlled directions. Although the method is designed for industrial assembly tasks, it does not take into account the presence of a human in the loop. In contrast, Erden and colleagues [25–27] have thoroughly studied an industrial task that directly involves a human operator, i.e., manual welding. In [25], a physically interactive controller is developed for a manipulator robot arm: the human applies forces on the robot, to make it behave as he/she likes. Then, a manual welding assistant robot is presented in [26]: as the human controls the welding direction and speed, the robot suppresses involuntary vibrations (e.g., caused by novice welders). The results show a considerable improvement in the welders performance when they are assisted. Finally, [27] presents a study of end-point impedance measurement at human hand, with professional and novice welders. The results support the hypothesis that impedance measurements could be used as a skill level indicator, to differentiate the welding performance levels. Although the welding assistance application targeted by these works also falls in the shared workplace paradigm evoked in [2], it differs from the one treated here, since the robot motion is driven by the human worker. Instead, in our work, the robot is active and autonomous during various phases of the assembly cycle. For the same reason, robot programming by demonstration/teaching is also out of scope here.

Other works similar to ours, but targeting manually guided robot operation, are presented in [28,29]. In [28], an operator teaches tasks to a robotic manipulator, by manually guiding its end effector. For this, the authors design a virtual tool, whose dynamics the operator should feel when interacting with the robot. An admittance controller driven by the measurements of a force/torque sensor is designed to ensure the desired virtual dynamic behaviour. The second paper addresses the problem of controlling a robot arm, executing a cooperative task with a human, who guides the robot through direct physical interaction. This problem is tackled by allowing the end effector to comply according to an impedance control law [30] defined in the Cartesian space. Redundancy ensures the stability of the coupled human–robot system, through inertial decoupling at the end effector. However, in

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[2] www.iso.org/iso/catalogue_detail.htm?csnumber=51330