



Flexible human–robot cooperation models for assisted shop-floor tasks[☆]

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ABSTRACT

The Industry 4.0 paradigm emphasizes the crucial benefits that collaborative robots, i.e., robots able to work alongside and together with humans, could bring to the whole production process. In this context, a yet unreached enabling technology is the design of robots able to deal at all levels with humans' intrinsic variability, which is not only a necessary element to a comfortable working experience for humans, but also a precious capability for efficiently dealing with unexpected events. In this paper, a sensing, representation, planning and control architecture for flexible human–robot cooperation, referred to as FlexHRC, is proposed. FlexHRC relies on wearable sensors for human action recognition, AND/OR graphs for the representation of and the reasoning upon human–robot cooperation models online, and a Task Priority framework to decouple action planning from robot motion planning and control.

1. Introduction

According to the Industry 4.0 paradigm, manufacturing is expected to undergo an important paradigm shift involving the nature of shop-floor environments. One of the main ideas put forth in smart factories is *getting closer* to customers, increasing their satisfaction through a high degree of personalization and just in time goods delivery. This poses serious challenges to shop-floor operators, in so far as work stress, fatigue and eventually alienation are concerned, with repercussions also on work quality and faulty semifinished products.

Among the recommendations to reduce such drawbacks on human operators, collaborative robots have been proposed to work alongside humans to perform a series of tasks traditionally considered stressful, tiring or difficult [1]. Clearly, this proposal implies a number of challenges related to human–robot interaction both at the physical and the cognitive levels of the cooperation [2–4], which depend also on their type [5]. Beside basic safety considerations, which are a necessary prerequisite [6], a number of key issues must be taken into account: sensing and human activity recognition [7], definition of suitable cooperation models to reach certain goals [8–10], robot action planning and execution in the presence of humans [4], and the effect of robot's predictable behavior on the operator well-being and performance [11], just to name a few.

Among the possible use cases where human–robot cooperation can be particularly relevant, we consider cooperative assembly as a

motivating scenario. If we focus on assemblage tasks, typically involving a small number of semifinished pieces, a number of difficult-to-model situations arise: the order of assemblage operations is often not strict, i.e., different sequences are possible and equally legitimate as far as the final result is concerned; an operator and a robot engage in a sort of turn taking process, where the robot is expected to assist and adapt to human actions at run-time; for a fruitful cooperation to occur, the operator and the robot must understand each other actions and intentions. These considerations can be synthesized in four functional specifications focusing on improving the operator's *working experience* [12].

F_1 [*Flexibility*] Operators should not be forced to follow a strict, predefined sequence of operations, but should be allowed to decide what actions to perform *on the fly*, subject to their adherence to the overall cooperation goals. As a consequence, robots should trade-off between providing operators with optimal suggestions about next actions to perform and reacting appropriately when operators do not follow such instructions.

F_2 [*Intelligibility*] While the cooperation process unfolds, operators should be capable of intuitively understanding robot actions and *intentions*, and this may be achieved at a symbolic, *linguistic* level of communication. Therefore, collaborative robots should be able to decouple action planning (whose results are meaningful for operators) from motion planning and control, the latter hiding low-level complexities associated with robot motions also when the

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workspace is partially unknown.

F_3 [Adaptability] In order for a robot to detect and classify meaningful actions carried out by an operator, it should not be necessary different operators undergo a specialised action modeling and adaptation process, i.e., the robot should adapt to them without requiring an operator-specific calibration process.

F_4 [Transparency] Operators should not be required to limit their freedom as far as motions are concerned, e.g., being forced to stay in front of a collaborative robot all the time, to have their actions duly monitored during the cooperation process.

In this paper, a sensing, representation, planning and control architecture for flexible human–robot cooperation, referred to as FlexHRC, is proposed. FlexHRC deals with the specifications outlined above by design, in particular enforcing flexibility at two different – yet related – levels.

R_1 Although robots suggest actions to perform based on *optimality* considerations and the goal to achieve, operators can choose an action without following robot’s suggestions [13], while the robot reacts to operators and plans for the next action accordingly [14–16].

R_2 Although robot operations are well-defined in terms of motion trajectories and, above all, intended effects, reactive behaviors allow for dealing with partially unknown or dynamic workspaces, e.g., to perform obstacle avoidance, without the need for whole trajectory re-planning [17,18].

To this aim, FlexHRC implements a hybrid, reactive-deliberative human–robot cooperation architecture for *assisted cooperation* [5,19] integrating different modules, namely: (i) human action recognition using *wearable sensors*, which do not pose any constraint on operator motions, to address F_4 , and exploiting statistical techniques for action modeling [20] to take F_3 into account; (ii) representation of human–robot cooperation models and online reasoning using *AND/OR graphs* [10,13,21] to deal with F_1 ; (iii) control schemes based on a *Task Priority* framework to decouple human–robot action planning from robot motion planning and control [18], therefore addressing F_2 .

The paper is organized as follows. Section 2 discusses related work. Cooperation models and the associated sensing, reasoning and robot motion processes are described in Section 3. Experimental results are presented and discussed in Section 4. Conclusions follow.

2. Background

During the past few years, human–robot interaction gained much attention in the research literature. Whilst approaches focused on cooperation consider aspects related to natural interaction with robots, e.g., targeting human–robot coordination in joint action [22–24], this analysis focuses on the human–robot cooperation process from the perspective of the functional specifications discussed above.

The problem of allowing humans and robots to perform open-ended cooperation by means of coordinated activity (F_1) did not receive adequate attention so far. An approach highlighting the challenge is presented in [8], where an execution planning and monitoring module adopts two teamwork modes, i.e., when humans and robots are equal partners and when humans act as leaders. On the one hand, a reference shared plan is generated offline, and actions are allocated to a human or a robot according to their capabilities. On the other hand, coordination is achieved by an explicit step-by-step, speech-based, human to robot communication, which makes the user experience cumbersome and unnatural in most cases.

The ability of robots to mediate between high-level planning and low-level reactive behaviors has been subject of huge debates in the past three decades. When it comes to human–robot cooperation, the need arises to balance the requirements of reaching a well-defined goal

(e.g., a joint assembly) and providing human co-workers with as much freedom as possible. A number of conceptual elements for joint and coordinated operations are identified in [15]. The authors propose a *minimalistic* architecture to deal with aspects related to agents cooperation. In particular, a formalism to define goals, tasks and their representation, as well as the required monitoring and prediction processes, is described. The work discussed in [4] significantly extends the notions introduced in [15] to focus on *social* human–robot interaction aspects (F_2). The architecture makes an explicit use of *symbol anchoring* to reason about human actions and cooperation states. An approach sharing some similarities with FlexHRC is described in [10]. As in the proposed approach, AND/OR graphs are used to sequence actions for the cooperation process. However, unlike FlexHRC, action sequences cannot be switched at runtime, but are determined offline in order to optimize graph-based metrics. As a matter of fact, the possibility of multiple cooperation models is provided for, although offline: optimal paths on the AND/OR graph are converted to *fixed* action sequences, and then executed without any possible variation. In a similar way, multiple cooperation models are considered in [13], where an AND/OR graph is converted to a nondeterministic finite state machine for representation, and later to a probabilistic graphical model for predicting and monitoring human actions, as well as their timing.

The development of sensing and control architectures able to integrate and coordinate action planning with motion planning and control is an active research topic. However, the challenge is typically addressed to deal with cases where planning cannot be guaranteed to be *monotone*, i.e., when sensory information must be used to validate the plan during execution [25]. Its application to human–robot cooperation tasks (F_3) has not been fully addressed in the literature. An approach in that direction is described in [26], where an integrated approach to Monte Carlo based action planning and trajectory planning via Programming by Demonstration is adopted in a scenario of toolbox assembly. Concurrent activities are formalized using a Markov decision process, which determines when to initiate and terminate each human or robot action. A multi-objective optimization approach for solving the subtask allocation for the project scheduling problem of HRC is introduced in [27], where an evolutionary algorithm takes care of real-time subtask allocation. The proposed framework considers both parallel and sequential features and logic restrictions as well as given objectives for human and robot action time and cost, idle time, etc.

Finally, a few approaches consider the issue of allowing human operators to retain a certain freedom of motion or action when interacting with a robot (F_4), but at the price of introducing a few assumptions in the process [28,29]. A Bayesian framework is used in [24] to track a human hand position in the workspace with the aim of predicting an action’s time-to-completion. The hand must be clearly visible for the estimate to be accurate, which limits certain motions. The opposite approach is adopted in [8], where an extended freedom of motion is obtained resorting to speech-based communication to indicate performed actions to the robot, as well as action start and end times. The obvious drawback of this approach relies on the fact that such a communication act must be voluntary, and therefore human stress and fatigue may jeopardize the will to do it. A more comprehensive approach is described in [4], which integrates human body position (determined by an external sensory system, e.g., motion capture), deictic gestures, gaze and verbal communication to determine a number of human actions. A gesture lexicon for giving commands to other partners in industrial environments is studied in [30]. The work investigates the gestures commonly performed by humans to communicate with each other about part acquisition, manipulation, and operation tasks. In the experimental evaluation, such gestures were replicated by an industrial robot and the understanding of human operators was measured. Both solutions rely on an *external* system for human activity recognition, which may be of difficult deployment in a shop-floor environment, and occlusions may occur nonetheless.

From this focused analysis, it emerges that although a number of

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