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Human–robot collaborative assembly in cyber-physical production: Classification framework and implementation

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ABSTRACT

The production industry is moving towards the next generation of assembly, which is conducted based on safe and reliable robots working in the same workplace alongside with humans. Focusing on assembly tasks, this paper presents a review of human–robot collaboration research and its classification works. Aside from defining key terms and relations, the paper also proposes means of describing human–robot collaboration that can be relied on during detailed elaboration of solutions. A human–robot collaborative assembly system is developed with a novel and comprehensive structure, and a case study is presented to validate the proposed framework.

1. Introduction

Industrial production is nowadays experiencing changes that shift the emphasis of production—and related R&D work—towards increasing flexibility and responsiveness of production processes, facilities and entire production networks. Among the drivers of these changes, the key objectives are decreasing desired lead time and growing customisation, leading to higher diversity and more frequent changes of products, components and tasks to be handled within the same production unit.

These trends are expected to affect the way both humans and machines are put to work—most importantly, the meaningful combination of human and robot skills is beginning to gain emphasis. The latter development aligns well with the shift towards more local autonomy in production processes: while certain routine tasks or specific skills can be efficiently supported by automation, local decisions or exceptional intervention often require a “human touch” due to the extraordinary characteristics of the given situation, the complexity, or the implicit nature of knowledge to be relied on in finding a viable solution in a limited time, with bounded resources at hand.

The combination of human and artificial resources has not been part of mainstream automation practice where (1) robots and humans are generally kept away from each other, and (2) humans must adhere to work procedures as rigid as the rest of the automated production environment. Symbiotic *Human–Robot Collaboration* (HRC) steps beyond these limitations but requires a more responsive, transparent and accessible environment backed by more computational intelligence [1–3].

Information and Communication Technology (ICT) has significantly changed assembly systems in the past years, partly due to the massive connectivity of components and actors (LAN, Wi-Fi, Bluetooth, near field communication, etc.), and partly due to increasing process observability and local computing capacity in smart devices (automatic identification, sensors, wearable devices, smart tags, etc.). The close and multi-directional interaction of virtual and physical entities forms a cyber-physical system where automated components and humans can be integrated in a cybernetic and collaborative environment combining their complementary strengths instead of mutual restriction of their potentials [4].

Robots exhibit high precision and repeatability, can handle heavy loads and operate without performance deterioration even in difficult or dangerous environments. However, robot control systems quickly reach their limits in recognizing and handling unexpected situations, as reflected by the relatively rigid plans and robot programs widespread in today's automated systems.

Humans tackle unexpected situations better, are aware of a much larger part of the environment than formally declared, and show more dexterity in complex or sensitive tasks. Humans, however, are more prone to error, stress or fatigue [5], and their employment underlies strict health and safety regulations.

With technologies able to bridge the gaps in skills and operational characteristics, it is now becoming possible to rely on robots as collaborating *partners* instead of—potentially hazardous—*tools* [6]. The appearance of off-the-shelf industrial robots certified for operating alongside humans is a sign of HRC gaining acceptance and spreading in industrial production.

Meanwhile the theoretical and technological supports for HRC are still undergoing notable development. A systematic approach to solutions involving HRC requires an efficient framework, and methodologies for elaborating feasible solutions. Contributing to

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these, the paper proposes a structured classification and solution framework, illustrated by practical examples.

2. State of the art in HRC and its classification

HRC research has been ongoing for decades, with service robots and vehicles operating in unstructured environment being the subject of most intense interest. Industrial production has been a minority field in this regard, partly due to health and safety regulations limiting HRC in practice. Yet, recent results indicate both the revision of established views and regulations, and intensified research of HRC in production scenarios.

2.1. Human–robot collaboration for assembly

Industrial robots had been expected to work as the assistant of human workers for a long time, comprising a fast and automatic assembly system and collaborative manufacturing environment [7]. Different robot and gripper structures are developed to assist workers on the assembly line. In general, most of the tasks focused on holding an object for the person, laying it aside or retrieving it on demand [7,8]. In recent years, the production engineering society also gave considerable attention to the collaborative systems in assembly lines. Human–machine and human–robot interactions have been identified as a feasible solution especially suitable for heavy and bulk component handling [9]. Morioka and Sakakibara [2] proposed an assembly system based on HRC. The cooperative parts feeding station is established based on information support and safety management mechanisms. At the control level, Krüger et al. [10] proposed a framework design for stable and robust interaction control. Intuitive programming mechanisms were developed for both online and offline programming via gestures and voices [11]. For the satisfaction of human needs, augmented reality was also deployed in the factory for virtual assembly, assembly guidance, training, maintenance, etc. [12].

2.2. Classification of human–robot collaboration

Answering the need for a systematic analysis of HRC requirements and adequate solutions, several considerations have appeared to classify or characterise individual cases [8]. Due to its specific constraints, industrial production usually occupies a mere subset of possibilities. While some characteristics are quantitative, most of the studies highlighted a small number of properties that define distinct classes of HRC instances:

- *Temporal and spatial relation* of collaborating humans and robots (*agents* in a more generic sense)—while this shows wide variation in cases like *teleoperation* or assisted vehicle steering [13], it is assumed in industrial production that the agents (partially) share the same space, even though their activity over time does not necessarily overlap [7]. *Close collaboration* with physical contact [14]—e.g., common handling of large workpieces—does, naturally, require co-location and simultaneous operation [15].
- *Agent multiplicity* can be covered to its full diversity by industrial HRC applications. Literature commonly distinguishes between *single*, *multiple*, and *team* (Fig. 1 left), the latter being a group acting by consensus or coordination, and interacting with the environment and other agents in a specified way (e.g., via a "spokesman"). Multiple agents can compete for resources and other agents' services (e.g., one robot serving several manned workstations).
- *Agent autonomy* and closely related *leader–follower relationships* express how much of robot action is directly determined by human agents, or which agent takes the lead in the given task. Partitioning along autonomy or initiative can vary depending on the application field [16]. In an industrial context, *inactive* (resting), *active* (leading), and *supportive* (following) behaviour can be distinguished, and many of the current considerations assume that these roles are assigned before task execution (Fig. 1 middle). In some cases, *adaptive* agents are also contemplated that assign leader/follower roles on-the-fly—these have gained little practical significance so far, and will be omitted in this paper.

Other aspects, such as modes of sensing, interaction, (mutual) awareness are typically treated as independent (orthogonal) characteristics that rarely form distinct classes.

3. Requirements of symbiotic HRC in assembly

3.1. Symbiotic HRC structure in assembly

Symbiotic collaboration is set aside from conventional HRC by several key characteristics:

- *intuitive and multimodal programming environment*: workers do not need prior in-depth knowledge of the system,
- *zero-programming*: ideally, the workers can work with the robots via gestures, voice commands, and other forms of natural inputs without the need of coding,
- *immersive collaboration*: with the help of different devices, e.g. screens, goggles, wearable displays, the workers can collaborate with the robots with actively engaged senses, and
- *context/situation dependency*: the system should be capable of interleaving autonomous human with robot decisions based on trustworthy inputs from on-site sensors and monitors inspecting both humans and robots.

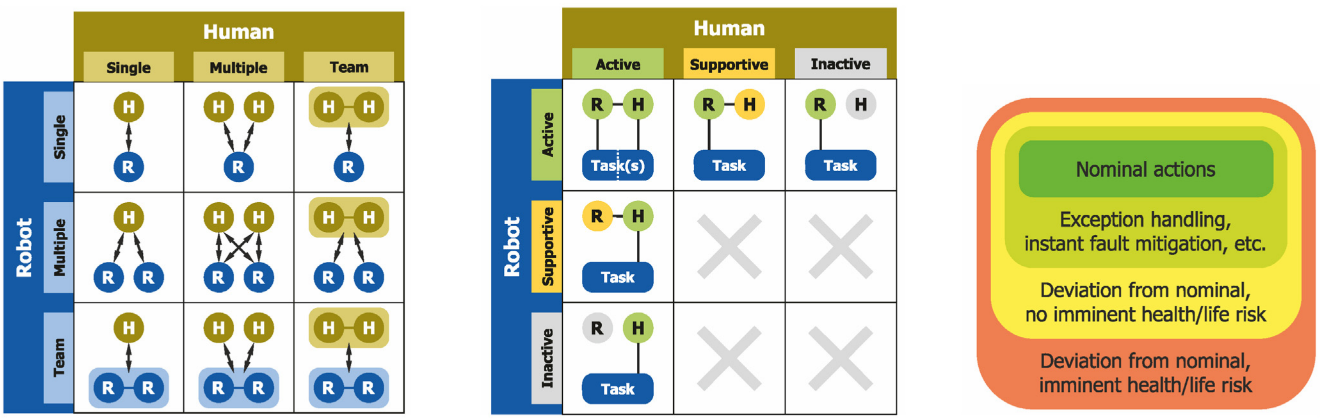

Fig. 1. Classification schemes of human–robot collaboration with regard to agent multiplicity (left), initiative (middle), and alignment of human actions with the nominal process definition (right).

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