Mechatronics 54 (2018) 94–109

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Mutual trust-based subtask allocation for human–robot collaboration in flexible lightweight assembly in manufacturing☆

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ARTICLE INFO

Keywords:
Flexible manufacturing
Assembly
Human–robot collaboration
Industrial robot
Hybrid cell
Subtask allocation
Trust
Robot vision
Visual interface
Prediction of robot behavior
Safety
Productivity
Quality

ABSTRACT

A human–robot hybrid cell is developed for flexible assembly in manufacturing through the collaboration between a human and a robot. The selected task is to assemble a few LEGO blocks (parts) into a final product following specified sequence and instructions. The task is divided into several subtasks. A two-level feedforward optimization strategy is developed that determines optimum subtask allocation between the human and the robot before the assembly starts. Human's trust in robot and robot's trust in human are considered, computational models of the trust are derived and real-time trust measurement and display methods are developed. A feedback approach is integrated into the feedforward subtask allocation in the form of subtask re-allocation if trust levels reduce to below specified thresholds. It is hypothesized that subtask re-allocation may help regain trust and maintain satisfactory performance. Experiment results prove that (i) the integrated (feedforward + feedback) optimum subtask allocation is effective to maintain satisfactory trust levels of human and robot that result in satisfactory human–robot interactions (HRI) and assembly performance, and (ii) consideration of two-way trust (human's trust in robot and robot's trust in human) produces better HRI and assembly performance than that produced when one-way trust (human's trust in robot) or no trust is considered.

1. Introduction

Global competitiveness in manufacturing is a challenging issue due to the requirements of high productivity and quality, low costs and highly skilled workforces [1]. Assembly in manufacturing significantly affects overall manufacturing productivity and quality due to extensive usages of labors, materials, utilities and maintenance in assembly operations [2]. Manual assembly is usually tedious, burdensome to workforces, inefficient and it affects worker's health and safety adversely [3]. Hence, automation of assembly should be prioritized, but it is usually expensive and inflexible [4]. We posit that appropriate collaboration between human and robot exploiting their complementary skills and competence can make the assembly more flexible, safe, cost effective and productive [5]. Recent advancements in lightweight low-cost flexible industrial robots, e.g., Baxter and Sawyer [6], Kinova [7], KUKA [8] have raised the possibility of such collaborations. This innovation is especially necessary for Small and Medium-sized Enterprises (SMEs) as such enterprises cannot afford highly expensive assembly automation due to financial limitations and frequent changes in assembly requirements.

Being motivated by the above prospects, Human–Robot Collaboration (HRC) in assembly has become an active area of research that has addressed different aspects of assembly in manufacturing, e.g., [9–13]. In [9], Tan et al. focused on design and development of HRC in cellular assembly in manufacturing. In [10], Wilcox et al. proposed optimization of temporal dynamics for adaptive HRC in assembly. In [11], Kaipa et al. presented HRC in hybrid cells for low volume assembly tasks. In [12], Sauppe and Mutlu proposed task training strategies for instructional robots for HRC in assembly. In [13], Gleeson et al. investigated gesture-based HRC in assembly, and so forth. The state-of-the-art initiatives (e.g., [9–13]) are undoubtedly helpful to promote the effectiveness of HRC in assembly. However, we still find two areas as follows that can add significant innovations and benefits to HRC in assembly, but have not received much attention yet:

1.1. Optimum subtask allocation

HRC in assembly can be executed in the form of a hybrid cell (a dedicated assembly space where a human and a robot can work simultaneously side by side without being separated from each other by physical cages) due to its various advantages such as convenient task allocation and scheduling and ease in resource mobilization,

☆ This paper was recommended for publication by Associate Editor Dr. Francesco Leali.

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https://doi.org/10.1016/j.mechatronics.2018.07.007
Received 3 July 2017; Received in revised form 11 May 2018; Accepted 19 July 2018

communication and supervision [11]. Subtask allocation in the hybrid cell for collaborative assembly divides the entire assembly task into several subtasks and assigns the subtasks to the human and the robot [14]. Subtask allocation is an important feature of the hybrid cell, which can affect overall assembly performance [18]. For subtask allocation, it is assumed that the task is divisible rather than unitary, which makes it possible that the human and the robot can work in parallel and no agent (human or robot) remains idle [15]. The main objective of subtask allocation is to minimize human's cognitive workload, improve situation awareness [16], increase team fluency [40] and safety [5], and maximize task performance (productivity, quality, etc.) [14]. Subtask allocation seems to be better than task transition between agents where one agent is always idle and thus reduces task inertia and efficiency [14].

Optimization of subtask allocation assigns right subtasks to right agents (human and robot) so that the overall performance is maximized through maximizing the utilization of resources and agent capabilities and minimizing agent constraints [17]. Suboptimum subtask allocation in collaborative assembly can reduce safety, productivity and quality, and sometimes the assembly cannot be performed at all [14–17]. Such problems can be more critical for high-mix and low-volume assembly lines with frequent changes in requirements [18]. However, optimum approaches to subtask allocation for assembly in manufacturing are rare except a few initiatives, e.g., [18–20,43]. Furthermore, effectiveness and practicality of these existing initiatives are not evaluated properly. A few task allocation methods have been proposed for other scenarios, e.g., space mission [14], satellite communication [46], multi-robot systems [17,47], multiple humans working with multiple unmanned aerial vehicles (UAVs) [16], etc. Optimizations of instantaneous and resource-based task allocation for multi-agent systems have also been proposed [21]. In addition, a plethora of well-established optimization techniques are available in the state-of-the-art literatures for various other purposes such as business risk analysis [44], business decision making [45], etc. However, the state-of-the-art optimization methods and strategies for task allocation and other purposes cannot be directly applicable to HRC in assembly for a few reasons as follows: (i) the roles are switched between the agents instead of dividing the roles between the agents [14], (ii) the ideas are not tested through actual HRC [18], (iii) the task allocations are between multi-robots [17,47], or multi-humans [16] instead of between a human and a robot, (iv) the techniques are good for business solutions, but may not be well-suited for assembly in manufacturing [44,45], and so forth.

The state-of-the-art task allocation strategies are of feedback type [18–20,43], i.e., the optimum subtask allocation is determined after the assembly or activity is performed. This optimization approach seems to be very reliable as it takes the information of the actual assembly/activity into account. However, it is not practical in industrial applications because the optimum subtask allocation needs to be decided at the beginning of the assembly, but actual assembly information is not available at this stage [26]. This problem emphasizes the feedforward optimization of subtask allocation where the optimum subtask allocation can be determined before the assembly starts [26]. We predict that such feedforward optimization can be performed based on the potential feasibility of the subtask allocation instead of on the actual assembly information. Nonetheless, a possible drawback of the feedforward strategy may be that the optimization results are not very reliable as the optimization is conducted based on the information of feasibility analysis instead of on the actual assembly performance. Considering the above dilemma, we posit that an integrated approach combining feedforward and feedback optimization of subtask allocation can be more beneficial than an individual feedforward or a feedback approach. We argue that, in the integrated allocation, the feedforward optimization can help start the assembly with optimum subtask allocation and the feedback optimization in the form of subtask re-allocation can modify the feedforward optimization if needed while the assembly is in progress [22,26]. However, initiatives for such integrated optimization of subtask allocation/reallocation in human–robot collaborative assembly in manufacturing have not received much attention yet except a preliminary initiative taken in [26].

1.2. Human–robot mutual (bilateral) trust in HRC in assembly

Human's trust in the collaborating robot is the willingness of the human to rely on or to believe in the cooperation provided by the robot [23]. A satisfactory level of trust is mandatory because the human may not find interest to collaborate with the robot if the human does not trust it [23,24]. Again, the human may be influenced by the institutional trust towards the robots [50]. A few studies on human's trust in collaborating robots have been proposed, e.g., [25], but these studies are preliminary and are not related to human worker's trust in robot in assembly in manufacturing. We observe mutual (bilateral) trust between two or multiple humans that plays a significant role in human–human collaborative task [41]. We also observe interpersonal trust in society [51], which is bidirectional. Hence, being inspired by such bidirectional trust in nature, we in addition to considering human's trust in robot, argue that robot's trust in collaborating human should also be considered for human–robot collaborative assembly. The bilateral trust between the human and the robot can make the collaboration transparent to the partners (robot and human). Such transparency can allow the human and the robot to alter some aspects of their behaviors based on their mutual trust levels that can enhance the predictability of one agent's actions and behaviors to another agent and thus can improve the team fluency [26,40]. Such predictions through trust can reduce human's cognitive workload as the robot's perceptions about the human become transparent through the robot's trust levels, and thus the human can devote more cognitive resources to the task instead of worrying about or trying to explain the actions and behaviors of the robot. The robot can also adjust its behaviors based on human's trust level to keep pace with the human. All these can enhance quality, productivity and safety in HRC in assembly in manufacturing [26].

In addition, bilateral trust status can be a criterion to decide subtask re-allocation between the collaborating partners, which can help regain trust. However, none have examined the possibility of giving the robot the ability to perceive its trust in its human collaborator for HRC in assembly except a few preliminary studies, e.g., [26]. As a consequence, it can cause uncertainty in the effectiveness of HRC in assembly even though the human and the robot start the assembly with optimum subtask allocation, which can affect assembly performance accordingly. Hence, bilateral trust between human and robot should be considered for HRC in assembly in conjunction with optimum subtask allocation. Again, trust depends on agent performance and faults, and thus the trust can change as the assembly progresses [27]. Hence, a computational model of trust is necessary to include it in the execution of HRC in assembly and in triggering the trust-based subtask re-allocation [26]. However, such computational trust models for HRC in assembly have not received much priority yet except the preliminary concepts proposed in [26]. Trust in task allocation was considered in [28], but the optimization strategy was not designed properly and it was not related to assembly in manufacturing. Hence, based on above discussion, it can be understood easily that modeling of human–robot bilateral trust, real-time trust measurement and display, mutual trust-based assembly and trust-triggered subtask re-allocation during assembly demand special priority for upholding the overall assembly performance. However, such initiatives have not received much priority yet.

Being motivated by the above limitations of the state-of-the-art research works on HRC in assembly in manufacturing, we decided the objectives of this article as to: (i) derive computational models for human's trust in robot and robot's trust in human, (ii) develop methods to measure trust in real-time (or near real-time), (iii) develop an integrated (feedforward and feedback) strategy of optimum subtask allocation between the human and the robot triggered by trust, and (iv) evaluate the integrated optimum subtask allocation in terms of