Mechanisms and Capabilities for Human Robot Collaboration

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Abstract— **This paper deals with the concept of a collaborative human-robot workspace in production environments recapitulating and complementing the work of the author presented in [1]. Different aspects regarding collaboration are discussed and applied in an exemplary scenario. Modalities including visualizations and audio are used to inform the human worker about next assembly steps and the current status of the system. The robot supplies the human worker with needed parts in an adaptive manner to prevent errors and to increase ergonomic benefits. Further, the human worker can intuitively interact and adjust the robot using projected menus on the worktable and by force-guidance of the robot. All these functions are brought together in an overall architecture.**

I. Introduction

Robots have proven their success since their introduction in the industry in the late 60ties – mainly because robots are reconfigurable and therefore applicable for a variety of tasks. Although robots are flexible and multi-purpose machines, their flexibility heavily reduces due to their static task programming. If the task, the product or the environment changes, their movements often need to be re-programmed from scratch. The costs of task-adequate robots and the effort to set-up, program, and integrate them into existing production lines amortize only with a large number of manufactured products, because the costs of the integration of a robot are approximately ten times the price of the robot itself [2].

Nowadays, as manufacturing industry is faced with increasing product variants while production cycles decrease, conventional strategies to optimize production steps are saturating. Future competitiveness of manufacturers will be highly related to their ability and flexibility to adapt to these essential market requirements [3]. This flexibility is at the moment hardly reachable with fully automated production processes. Especially, if small lot sizes of units or prototypes with a high variety and high task complexity are needed, current automation strategies are not cost efficient [4].

The collaboration between human and robot has been announced as a promising approach to solve these challenges, because it teams the strength and the efficiency of robots with the high degree of dexterity and the cognitive capabilities of humans into a flexible overall system. As consequence of current flexible automation techniques including *flexible manufacturing systems (FMS)* and *reconfigurable manufacturing systems (RMS)* [5], a recent trend in robotics focuses on new generations of robots with the capability to directly assist humans. This bridges the gap between fully automated systems and fully manual workstations [6]. Highly related is that a significant amount of research has been done in the area of physical human-robot interaction (pHRI) [7], [8] that can also be applied to collaborative tasks between human and robot. Additionally, the introduction of cognitive capabilities [9] for assistive robotic systems, new robot control schemes, and advances in artificial perception, to name only a few, are enabling factors to bring human and robot further together in a shared workspace. Especially, technical systems need to improve their performance with respect to unforeseen events, flexibility in their use, and field of application through cognitive capabilities [3]. This creates more flexible and (partly) autonomous machines that are able to directly cooperate and support the human co-worker [10], [11]. Further, keeping the human *in the loop* of production processes for highly flexible assembly advances the skills of the overall system due to cognitive and sensomotoric advantages of the human. Hence, the human is part of production processes when he is needed and can concentrate on other tasks to improve the overall system performance [12].

The support of humans by robotic systems can then lead on the one hand to more ergonomic work places and on the other hand to more time-efficient production processes. Additionally, the amount of fixed production costs in relation to variable costs can be reduced [13]. The advantage of the potentials for humans and robots to work together as a team is only in early stages and needs a safe, robust and efficient realization [14]. Once this is reached, the subsequent flexibility and adaptability of human and robot collaborating as a team allows production scenarios in permanently changing environments as well as the manufacturing of highly customized products in *factories of the future*.

This paper recapitulates and complements the work of the author published in [1].

II. Collaborative (industrial) robotic systems

Robotic systems that assist human workers in production processes as well as in production environments are an active research field with a variety of applications. The following overview gives an impression about systems that have been introduced in the past to tackle human-robot collaboration in the production.

A robotic system consisting of multiple impedance-controlled robots is introduced by Kosuge in [15]. With this system, a joint object manipulation of human(s) and (multiple) robot(s) in a dynamic way is possible. The control scheme assumed that the interaction takes always place through an object. A force sensor attached to the wrist of

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each robot measured the external forces on the robots through the object. The human commanded the movement of the robots by applying forces to the object. This approach was later extended to the mobile robotic assistant *MR Helper* as presented in [16].

Khatib presented in [17] several strategies to support workers in physical tasks for compliant motion and cooperative manipulation. In addition to the controlling of multiple arms corresponding to the applied forces, multiple holonomic mobile platforms were coordinated to have a fully flexible mobile assistant.

For situations that involve large interaction forces as it is for example present in the automobile production, *Cobots* have been introduced by Colgate in [18]. These specialized mechanical devices provide guidance to human operator's motion. The *cobots* act passively with virtual fixtures and virtual walls to support and guide the human collaborator without the intention to act autonomously.

PowerMate—introduced by Schraft in [12]—is another example of a system designed to give the human worker a robotic assistant for handling and assembly tasks. The system follows current safety norms and works with normal velocity, if no human is present. In presence of a human, the velocity is limited and with the confirmation of the human, the robot can be guided to place heavy good using force/torque sensing. With this mode, it is possible to pull the robot on its gripper to a desired position.

A rather application oriented approach to ease and speed up the programming of industrial robots is presented by Pires in [19]. The approach is object-oriented and based on a client-server architecture. It is claimed that the underlying concept is general enough to be applied to organize and program overall flexible manufacturing cells.

Flexible, adaptive, and *cognitive* robots are especially needed, if small lot sizes of units or prototypes with a high variety and high task complexity are required. That means, that future industrial robotic assistants should be flexible and safe on the one side and *clever helpers* in manufacturing environments on the other side. Hägele describes this in [14] as the evolution *from robots to robot assistants*. To show the concept presented in [14], the mobile robot assistant *rob@work* has been developed by Helms and Hägele [20], [21] as direct interacting and flexible device for assistance. The collection of functionality includes automatic path planning, obstacle avoidance, precise positioning, and several safety concepts of the robotic arm motions. Further, the ease of use to instruct tasks was demonstrated.

A cooperative assembly cell system using a four-axis scara robot was presented by Thiemermann in [22], [23]. The system enhanced standard tasks of the assembly robot with new functionality to help the human worker with the workpiece positioning or with other parts and tools. A camera-based system is used to adapt the working velocity of the robot according to the distance between human and robot.

A mobile assistive robot for flexible and interactive manufacturing is presented by Stopp in [24]. Due to safety aspects, the human instructor teaches interactively the robot an order-picking from outside its workspace using a laser pointer and a handheld computer. This has been extended to a safety concept using dynamic sensor-based surveillance of the robot workspace and multiple safety regions with (possibly) different safety levels [25].

Iossifidis presents in [26] the stationary 7 dof robotic assistant *CoRA*, that is able to cooperatively solve an assembly task using diverse inter-connected components including speech, object, and gesture recognition. Additionally, the robot has been prepared with an artificial skin to allow a touching and positioning of the robot by the human.

Gecks presents in [27] *SIMERO*, a stationary industrial robot system. Several stationary cameras that detect obstacles to dynamically adapt motions accordingly supervise the workspace of the robot. This approach has later been enhanced by the use of multiple depth cameras [28] to perform a three-dimensional collision avoidance for unknown objects. One master computer evaluates the synchronously acquired data of slave computers and employs a geometrical model to revise the data points and to adjust the robot velocity according to distance of human and robot. In this way collisions with obstacles or the human can be damped or even prevented.

A pro-active collaboration between human and robot based on the recognition of the intentions of the human is described by Schrempf in [29]. As the recognition of intentions is quite uncertain, the robot resolves this uncertainty by pro-active execution to minimize the overall costs. For the system, Dynamic Bayesian Networks (DBNs) were used.

The approach by Rickert presented in [30] describes a scenario in which a human and the *JAST* robot—a robot with two arms in a human-like arrangement—build together a wooden model of an aircraft using a distributed architecture divided into the high-level components *input, interpretation, representation, reasoning,* and *output* with several functional modules.

Another example is the DLR lightweight arm presented in [31], [32] that was transferred to KUKA[1] and is now commercially available. This lightweight robot is especially designed for interaction with unknown environments and with humans [33]. The integrated compliance, virtual fixtures, high interpolation rate, and many more make the robot very promising to work alongside with humans. Haddadin uses this arm to build a sensor-based robotic co-worker for a safe and close cooperation and presents strategies for safe interaction with the human [34].

Chuang presents in [10] a study on human robot collaboration design for robot assisted cellular manufacturing and identifies that collaboration planning, collaboration safety, mental workload management, and a good man-machine interface as four main concepts that need to be met to enable human robot collaboration. Further the authors present in [35] experiment evaluations of different supportive information formats and show, that it is important to display information near relevant object and in the visual attention

[1] `http://www.kuka.com`

field of the human. Additionally, the combination of information sources such as text and images is important.

III. Psychological aspects

To successfully integrate collaborative assembly systems in today's processes, high demands regarding safety, efficiency, ergonomics, flexibility, programmability, and adaptability need to be met. As humans being experts in physical interaction and collaboration, the investigation of high-level joint-action strategies between humans is important to find strategies for robotic systems [36]. Further, the research on especially humanoid robotics can on the reverse side also contribute to understand how humans behave [37]. Psychological research on cognitive processes of joint-action among humans [38] lists *task sharing, joint attention, action observation* and *action coordination* as important mechanisms that influence the efficiency:

- *joint attention* to steer ones concentration and to share representations about events and objects
- *task sharing* to be able to predict the next steps based on the expected behavior of the opponent before an action can be observed
- *action observation* to predict the next goal based on the current behavior of the opponent
- and *action coordination* to adjust own actions in space and time to the behavior of the opponent

That means, that in collaborating human-human teams, an efficient coordination requires participants that plan and execute their actions in relation to what they expect from the opponents based on observations [39]. Action of the team members are observed and *evaluated* to coordinate own actions appropriately in space and time. Hence, humans negotiate unconsciously various parameters to optimize the co-operation during the collaboration [40]. During repetitions of the same action, the coordination becomes smoother and more accurate and leads to a maximum in comfort and efficiency.

Additionally, enabling factors are the abilities of the system to act autonomously in the environment according to sensor and context information. The communication and the explanations from the assistive system should also follow psychological aspects to decrease the distraction and the cognitive load of the human [41], [42].

Further, technical systems should make use of information provided by multiple sensors, (multiple) actuators, that are embedded in and aware of the *real world* to perceive, reason, learn and plan in a cognitive way. Along with reflectiveness about their own capabilities and limitations, cognitive technical systems know *what* they are doing, *how* things can be done, and *about* the human collaboration partner. This leverages higher flexibility, adaptivity, interaction and collaboration capabilities of the systems [43].

Another important issue constitutes, that collaboration of partners can be defined as being based on achieving a common goal together with commitments of every participating partner. This differs significantly from short-term interaction, where partners have no shared (long-term) goal [44]. Although, it is hard to distinguish these two terms in many cases at first glance, the difference becomes clear if errors occur: partners that act jointly and collaborative with the same global goal in mind can support each other and assist, because both know *what* needs to be done [45].

Therefore, to manage a predefined goal—e.g. the joint assembly of a product—the robot-system needs to know about the task in the production process as well as the human worker (*task sharing*). If the representation of the subtasks is as generic as possible, the role allocation can dynamically change even during the execution. A common representation of human and robot capabilities is an important issue in order to assign tasks according to specific skills [46]. With the knowledge about a shared plan, the system is able to predict possible next action steps and prepare these steps pro-actively.

For cooperation between robot and human, it is important that both partners coincide on the same objects and topics and create a perceptual common ground with a shared representation [38]. Considering *joint attention*, the system needs to have the ability to control the focus-of-attention of the human to direct to relevant objects or has to be able to estimate the human's focus-of-attention directly. This can also include pointing gestures as integrated in [30] or the head orientation of the human worker.

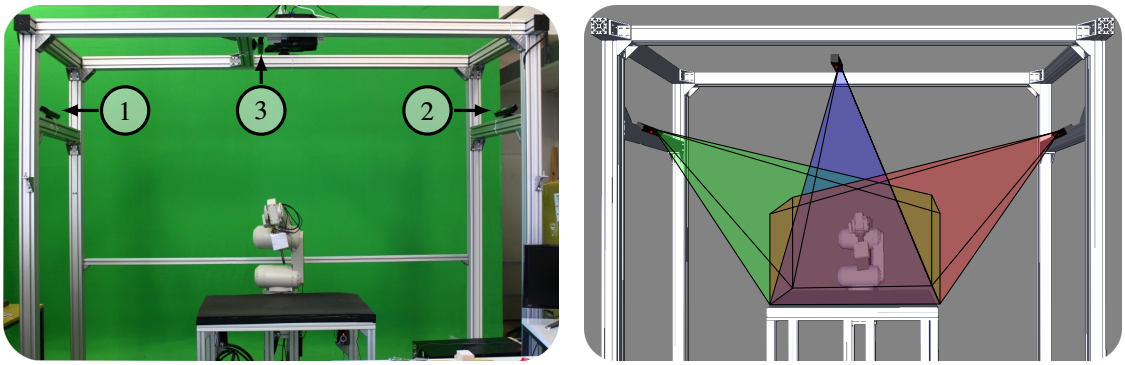
The transfer of these basic mechanisms of joint-action to a robotic assistive system can improve the collaboration of human and robot. This also includes the unconscious adaption of own actions using anticipatory knowledge about the actions of the team member and the recognition of what the team partner is currently doing. The benefit of transferring anticipatory action to a human-robot context is also shown in [47], where a significant improvement of task efficiency compared to reactive behavior was possible. For an extensive evaluation of these hypothesis, we want to refer to previous publications [1], [48], [49], [50].

IV. Implementation

The mechanism to enable a collaboration between human and robot described in the previous sections require certain capabilities of the system. We see perception, recognition, dynamic and adaptive motions, and communication as central capabilities for a human-robot collaborative system. Therefore, we have implemented and evaluated these capabilities as follows:

A. Capability: Perception

Knowledge about the static and dynamic situation is essential for joint workspaces of human and robot. Surveilling the joint area helps to realize a collaboration and co-existence of human and robot. Therefore, we have propose in [51] a system that redundantly monitors the workspace to perceive obstacles within the workspace including the human worker. We use multiple, distributed range sensors (i.e. Microsoft Kinect) and de-centrally pre-process the data from the sensors. These data sets are further processed and segment and



(a) The *JAHIR* set-up (b) Visualization of the *JAHIR* set-up

Fig. 1. Positions of Kinect sensors. Kinect devices 1-3 are installed on a scaffold surrounding the workbench (a). The devices are also integrated into the three-dimensional simulation of the set-up (b). The view areas of the devices that are of interest for the workspace surveillance are also highlighted in (b)

cluster unknown objects. The system finds and segments individual object point clusters in the acquired point clouds. For each detected object point cluster, a convex hull is computed which approximates the shape of the underlying object. The detected objects are then integrated into the global environment model. With the help of the integrated filtering methods, the system is able to distinguish between the static environment, the robot and other obstacles in the surroundings at high update rates. The gained geometric information can then be used in the robot controller to allow the system to react accordingly.

B. Capability: Recognition

In [52], we have presented a Hidden Markov Model (HMM) based workflow analysis of an assembly task jointly performed by a human and an assistive robotic system. In an experiment subjects had to assemble a tower by combining six cubes with several bolts for their own without the influence of a robot or any other technical device. To estimate the current action of the human, we have trained composite HMMs. After the successful evaluation on disjunct experimental data sets, the models are transferred to our assistive robotic system, where the same assembly tasks was executed. A new 3D occupancy grid approach was used to determine the hand positions of the worker. The positions were then used to compute the inputs of the analysis HMMs. The workflow of the right hand could be recognized with an accuracy of 92.26

C. Capability: Dynamic and adaptive motions

In [49] we have presented investigation on the influence of different hand-over timing strategies on the fluency and efficiency of such a human-robot team. Four different timing strategies were experimentally per- formed with 37 volunteers: (I) a fixed time interval between two hand overs, (II) a reactive behavior, where the robot is triggered by the human, (III) a fixed time intervals depending on the current component, and (IV) a predictive assembly duration estimation algorithm. During the experiment, the time- to-completion of the task and the waiting times for human and robot were measured as reciprocal indication for the efficiency and respectively the fluency of the team. The evaluation of the experiment indicates that the efficiency of the human-robot team is significantly increased using a predictive timing strategy, because it enables the robot to provide the subsequently needed component just-in-time. The decrease in waiting times for both human and robot approves increasing fluency of the collaboration. Additionally, the time prediction provides the opportunity to perform additional tasks with the robot, while the worker is occupied. Hence, nearly a full use of both partners' capacity in a assembly scenario can be achieved.

D. Capability: Communication

We have equipped our system with a variety of modalities to communicate with the human worker. On the output side we have

- a text-to-speech module to instruct the human and to give feedback
- an on-table projection to adaptively instruct the human and give feedback about the system status
- the adaptive robot itself, that is adaptively acting (see above).

On the other hand, the human has different possibilities to interact with the system. We have implemented

- a force control to adjust the robot
- a module that surveils the workspace and tracks the human (full body)
- virtual projected buttons and menus to (high-level) control the robot and the assembly process

V. Conclusion

In this paper, we have recapitulated on mechanism of human and robot collaboration and their instantiation through different capabilities to keep the human in the loop. The capabilities have been partly evaluated in previous work of the author. With this paper, the results are brought together in a broader context of joint human-robot action. An instance of the evaluation platform is depicted in the images of figure 2. A video showing the integration into the system in a joint collaboration can be found here: `http://www.youtube.com/watch?v=GpXkEd6y1LE`.

(a) (b)

Fig. 2. Human Robot Collaboration Plattform. The human can interact with a collaborative robot in a natural manner. The workspace is augmented with multiple screens showing the system status and instructions to the human. (a) The human receives a part from the robot. (b) The human can interact with the system using virtual buttons projected on the work desk.

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