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A Step Forward in Human-Robot Collaboration – The Project CollRob *

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Abstract
*Human-robot collaboration is a novel, hot topic in the field of industrial and service robotics with considerable potential. It offers the possibility to combine human cognitive abilities with the strengths of robot technology in terms of precision and performance, thus opening up a wide range of possibilities beyond the traditional application of robots. The research project "**Collaborative Robotics" (CollRob)** is an initiative focusing on the conceptualization, research, development, and evaluation of novel methods and tools for collaborative and cooperative robots. This article aims at giving an overview about this project in terms of its backgrounds, objectives, and the current status of research covering topics such as machine perception, sensitive redundant kinematic manipulation, dynamic adaptive planning, human-robot interaction and information exchange, human factors, and safety.*

1. Introduction

Since the introduction of robots to factories, approximately 50 years ago, their strength has been to perform well specified and repetitive tasks in constrained environments. Due to the high configuration and programming efforts in addition to significant investment costs, such an approach can only be profitable at large scales. However, current developments in modern production show a trend towards individualized manufacturing and thus small series in robot exploitation. Accordingly, novel innovative strategies and methods are necessary to allow for more flexibility in the production environment. In this context, one highly promising approach is human-robot collaboration [9]. According to this concept, humans and robots shall be enabled to jointly work together in the production process in order to combine human cognitive abilities with the strengths of robot technology in terms of precision and performance [2]. To make such a collaboration efficient and safe, a large range of challenges has to be addressed including topics like machine perception, sensitive redundant kinematic manipulation, dynamic adaptive task planning, human-robot interaction and information exchange,

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human state evaluation, and safety standards. These challenges are addressed in the 4-year research project ”Collaborative Robotics” (CollRob), launched in 2015[1]. In this article, an overview about the backgrounds, objectives and current status of this project is given, which shall serve as a reference for proceeding publications and research initiatives. Chapter 2. describes the elaborated hardware and software architecture of the overall CollRob system. Chapter 3. presents different specified levels of complexity for human-robot collaboration as well as envisioned use cases to test developed concepts and methods. Chapter 4. outlines concrete research challenges addressed within CollRob. Finally, Chapter 5. gives a conclusion.

2. Robot System Hardware and Software Architecture

To enable collaboration between a human and a robot, a variety of sensors is required. Figure 1(a) shows an overview of the CollRob hardware setup. Besides the robot itself, which is equipped with torque sensors, we use dedicated visual and proximity sensors for i) monitoring of the workspace and ii) detection and tracking of the human. In addition, we use wearable bio-sensors and eye tracking glasses to monitor the behavior and state of the human. A tablet, augmented reality (AR) glasses, microphones, speakers, and gesture bracelets are used as human-robot interaction devices.

The broad range of different sensors and devices results in complex data-flows, which in turn cause strong dependencies and couplings between the individual application parts. A software architecture for an application like this needs to relax the strong dependencies in order to enable re-usability, scalability and easy exchange of individual modules. Publish/subscribe has proven to be a well suited architectural pattern to accomplish this decoupling. An application is composed of modules which provide data (publish) and consume data (subscribe) from others. However, the transport of this data is handled by a dedicated infrastructure such that the modules need not know providers and consumers of their data. Figure 2 shows the modules which compose the CollRob system. In our architecture, each module is modelled as publisher and/or subscriber. We realize the publish/subscribe system using the Robot Operating System (ROS).

3. Levels of Complexity of Human-Robot Collaboration and Use Cases

Within the CollRob project, different levels of complexity of collaboration have been specified (see Table 1). The category A is in fact non-collaborative. However, taking it into account can be useful for setting up the general CollRob system architecture before going into collaboration details. The categories B to D consider human-robot interaction with gradually increasing complexity. Category E describes the case of two collaborating robots (or one robot with two arms) and category F the interaction between two robots and one or more humans.

category	**A**	**B**	**C**	**D**	**E**	**F**
umbrella term	encapsulation	H-R co-existence	static H-R collaboration	dynamic H-R collaboration	static/ dynamic R-R collaboration	static/ dynamic H-R-R collaboration
interaction level	interaction-free operation	safety stop	static collaboration	dynamic collaboration	static/ dynamic R-R collaboration	static/ dynamic H-R-R collaboration
actors	robot	human+ robot	human + robot	human + robot	2 robots	2 robots + human(s)
temporal dependence	independent	interrupt	sequential	simultaneous	sequential/simultaneous	sequential/simultaneous
spatial dependence	separated	separated	shared	shared	shared	shared
human-robot contact	none	rudimentary	pronounced	comprehensive	n.a.	pronounced/comprehensive

Table 1. Overview of interaction categories

Concerning the described categories, different application domains will be addressed in CollRob

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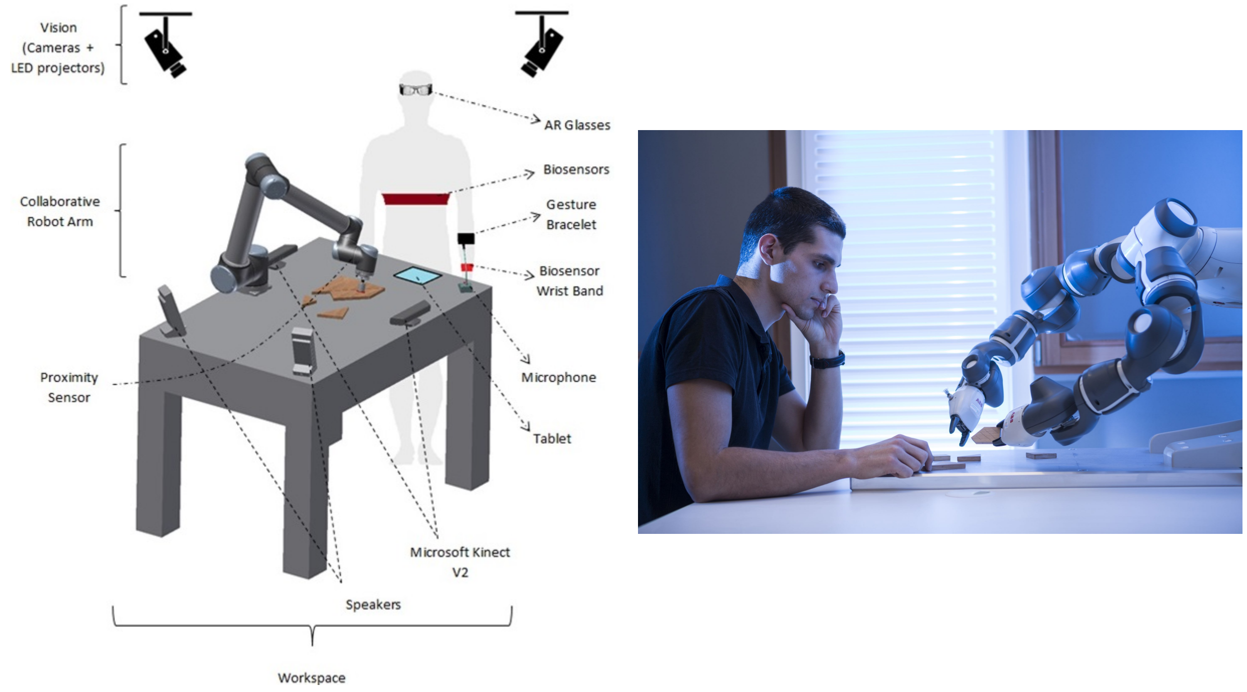
[1] http://www.joanneum.at/en/robotics/reference-projects/collrob.html



(a) Overview of hardware setup

(b) Human-robot collaboration to build a Tangram puzzle

Figure 1. Overview of hardware setup for puzzle solving

(e.g., industrial applications, entertainment applications, service applications, assistive technology applications). Concerning the applications of choice, it was decided that at least one ”set of use cases” should be chosen for which it was possible to carry them throughout all possible categories (A to D plus optionally E and F) by continuously extending and adding ”human-robot collaboration features”. The use case set of choice for this purpose is to solve a Tangram puzzle while the robot and the human are cooperating toward the goal (see Figure 1(b)). Further use cases, in collaboration with industrial partners, address industrial applications such as human-robot joint assembly and inspection tasks.

4. Addressed Research Challenges

4.1. Dynamic Working Environment Monitoring and Safety

In order to perform a safe and reliable collaborative task in complex and dynamic environments, a robust monitoring system, which provides a real-time status of the target area, is required. Methods from 2D [14] and 3D [24] quality inspection (and combined [29]) can be applied to robotic scenarios as long as sensors are lightweight and compact enough to be used on moving parts of the robot. 2D inspection is sufficient in case of close-to-planar objects. 3D shape comparison e.g., by Iterative Closest Point (ICP) [23], is a robust method in industrial inspection for irregular objects. Texture-based methods are complementary in case of smooth 3D surfaces that do not allow a precise 3D alignment due to shape ambiguities [5]. One major current application for such techniques is the inspection of correct 3D shape, the automatic planning of grasping is still a very rare application under real production conditions. Within CollRob, we use various optical sensors for localization, detection, 3D reconstruction, and depth estimation. The overall system has to cope with challenges such as submillimeter position accuracy for robot grasping, occlusion, surface reflections and complex shapes.

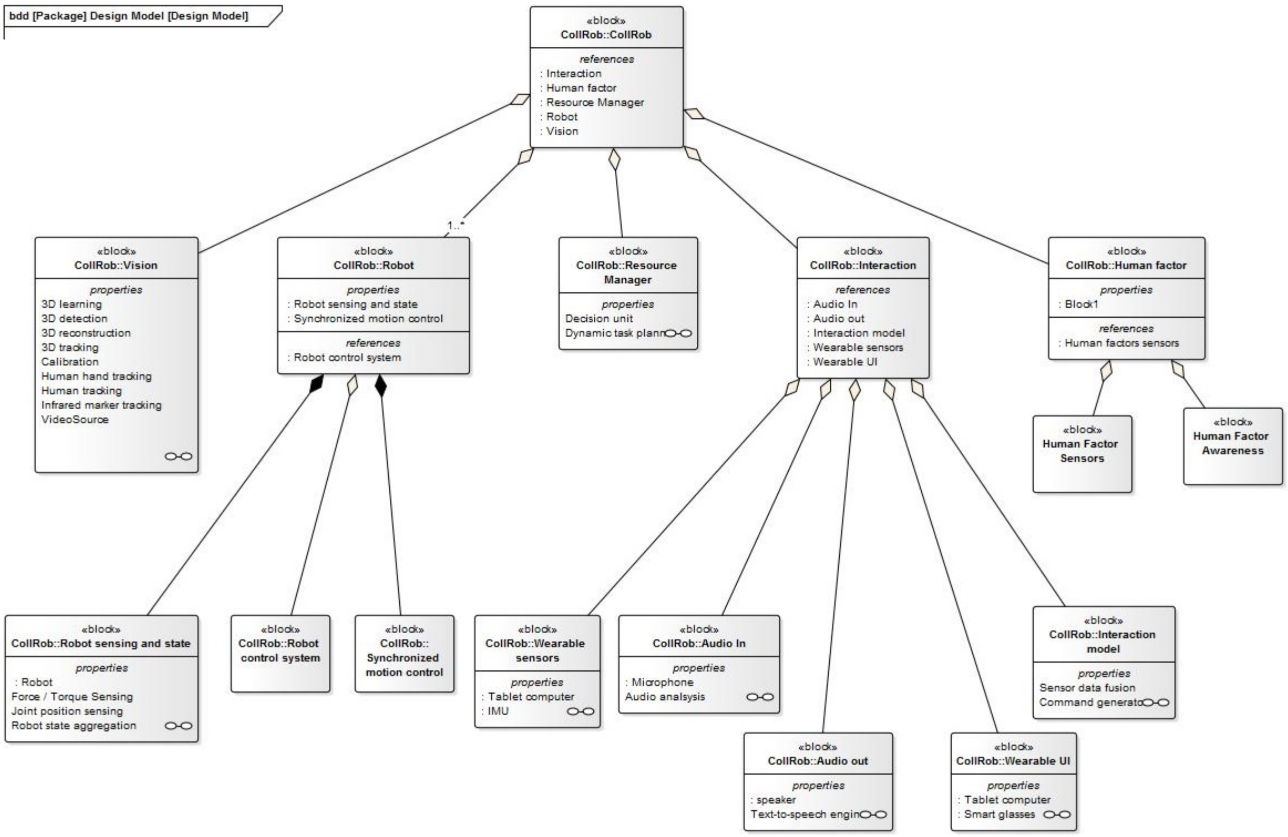


Figure 2. Structure of application modules

The system design fuses the information acquired from the various sensors: (1) Laser scanning (stationary) is used for large-scale mapping of workspace environment. (2) A 3D-Time-of-Flight (TOF) sensor is used for rough dynamic characterization of the scene. Alternatively, an additional stereo camera system with wider FoV can be used. (3) For high-resolution localization & inspection within the workspace of the robot (in order to achieve the required 0.05 mm resolution at specific parts of the scene), an active stereo system with an additional pattern projection unit is used. (4) On one of the Pan-Tilt Units (PTUs) used for sensor pointing, in addition a laser speckle projector is mounted to enhance texture-less regions for high-resolution stereo analysis. (5) All components of the sensor system will be integrated in one unit which allows quick installation and setup in the production environment.

We can benefit from such a system along with other sensory data for safety assurance [16]. Safety is one of the most important factors when considering human-robot collaboration in industrial applications. Various safety features such as vision, proximity sensors [33], laser detectors, touch and collision sensors, force torque sensors, and emergency stops could be exploited to achieve this goal. At the same time, many standards and guidelines throughout the design, robot manufacturing, installation, and final implementation are issued to increase the safety in the system [15, 1]. To provide safety, we need to cope with the sensor failures and their occlusion and also dynamic environments. To achieve this goal, we plan to build a hybrid safety system, which combines multiple safety features and sensors together in multiple layers in a both serial and parallel manner. This way, failure of one sensor will not necessarily compromise the safety as long as other components continue to function.

4.2. Analysis of Human Behaviors, Emotions and Actions

Humans generally interact with robots in the same way they might interact with other people, establishing social relationships and emotional ties with them [4, 8]. As industrial robots are enabling human and robot workers to work side by side as collaborators in manufacturing tasks, a fundamental issue regards the development of methods to assess the user's experience with a robot, while understanding how humans feel during their interaction with it [27]. Furthermore, human-related variables are essential for the evaluation of human-interaction metrics [26]. To work seamlessly and efficiently with their human counterparts, robots must similarly rely on predictions of the human worker's behavior, his/her emotions, task specific actions and intent to plan their actions. In [12] for instance an anticipatory control method using a human-in-the-loop architecture was implemented that enables robots to proactively perform task actions based on observed gaze patterns to anticipate actions of their human partners according to its predictions.

In the project CollRob, there is a focus on advancing models of human-related variables that directly refer to the evaluation of levels of autonomy in human-robot interaction, such as situation awareness, trust and workload, which have a long history in the automation literature [3, 6, 31]. CollRob undertakes to elaborate situation awareness in the manufacturing domain of human-robot interaction (HRI) on the basis of human attention measures. It specifically considers the dynamic estimation of current and predicted gaze in the context of collaboration affordances. Affordances have already been thoroughly studied in robot control [22]. However, from the human worker's viewpoint in the manufacturing domain, affordances refer to relations between the human and the manufacturing environment that, through a collection of stimuli, afford the opportunity for the worker to perform an interaction. CollRob intends to estimate various levels of human attention in the 3D environment [20] – in the context of collaboration affordances – and from this become capable to derive parameters for decision making: as low levels of situation awareness would decrease speed in safety-critical task processing, high levels would need to increase the throughput or to increasingly consider production quality related processing. As a first step, CollRob developed methodologies for the efficient, robust and low-cost method for the continuous localization of human gaze in industrial work cells. One application is to estimate gaze directly from eye tracking glasses based on the visual recognition of artificial random dot markers [28]. Additionally, a spatiotemporal model of attention was developed that estimates human gaze solely from egocentric vision [21]. Further activities in the frame of human behavior measurements will focus on the worker's context being estimated from psychophysiological measurements [27] and developing a metric for HRI situation awareness in the manufacturing domain.

4.3. Resource Managing including Dynamic Task Optimization and Decision Making

Human-robot collaboration requires robust and time-aware dynamic planning and scheduling strategies for robot-human teams. In the last few years, key contributions to make robot-human team collaboration more fluent stem from [25, 18]. Within the CollRob project, we will focus on the development of algorithms to deal with geometric issues, consider time based planning strategies and provide a robust implementation. Currently, our focus is to find a robot model for geometric and time-aware scheduling strategies by building a puzzle together. Our long term research goal is to deeply integrate the social interaction models (e.g., the fair distribution of team members, conflict solution strategies etc. for individual team members). A key issue will now be how we model such aspects.

4.4. Human-Robot Interaction and Information Exchange

Current research on HRI investigates different ways how robots and humans interact, the main ones being voice control [13], interaction primitive [7], motion recognition [10], force adaptation [17] and shared presence [30]. However none of these methods is well established in commercial applications. In this project, we focus on new paradigms of HRI in the context of collaborative industrial robotics and emphasize the distinction between collaboration and other forms of human-robot interaction, which usually view the problem as robot control or human-robot communication via tele-operation [11]. We include natural interaction mechanisms (acoustic and gestural interface), human factors [32] and a visualization component supported by augmented reality functionalities in an intelligent, context-sensitive control system. While human collaborators primarily interact using speech and gestural input, they receive situation-dependent information about current and future tasks, the robot's movement path and possible dangers. Here we explore the use of a head-worn AR system to ensure unobtrusive, hands-free collaboration and explore the optimal information flow to avoid cognitive load and distraction from the task. Moreover, the physical state of the human affects both the robot behavior and the feedback channel. This all strengthens the collaborative aspect of the interaction by increasing communication quality, trust, security awareness, and work efficiency. Recently, a first implementation of the interaction system was set up including the speech interface, a basic dialogue manager and a tablet application, serving as basic sensor interface. The human collaborator is thus able to interact with the robot using speech input, including basic robot task queue manipulation commands, while monitoring the sensory data. As a next step, the acoustic interface will be extended to include natural language understanding together with a more advanced dialogue manager. Moreover, a tablet application and wearable sensors will be used to analyse behaviors, emotions and actions of human collaborators. We will use the results of this analysis to implement the context-sensitive visualization and control system.

4.5. Redundant Sensitive Robotic Manipulation

Whenever a physical human-robot interaction is supposed to take place to fulfill a shared task, human ergonomic operation and safety are important aspects which must be observed. Robot safety is provided by the electromechanical system in different ways and often in a redundant fashion. In practical terms, the main options to reduce the risk of human injuries are safety-related monitored stops, speed and separation monitoring, and power and force limitations, as manifested in [ISO/TS 15066:2016]. The implementation of these options is done (i) by measuring the direct energy transfer between the robot and an object or (ii) by monitoring the environment using electromagnetic or sound based sensors. More specifically, a physical contact can be recognized by measuring the force, torque or current at the end effector, the robot's base, or at each joint. In addition, a sensitive skin applied on the manipulator can measure a contact force as well. If a direct contact is not desired, the environment can be perceived by different sensors operating at distance (see Section 4.1.). All sensor data can be fused to expand the knowledge of the environment, thus being used to control the robot's movement in a human-safe manner. That means that the dynamic movement of the robot must be planned and executed in an adaptive and reactive way.

If a kinematically redundant system has to perform a given task, the additional freedom can be used to enhance safety (by increasing the distance of the manipulator's parts to a human or reducing the velocity of the robot's arm segments) and ergonomics for a human operator (by configuring the robot joints in a way that the robot does not disturb ergonomic human motion). Such systems allow a change of the manipulator configuration without influencing the end effector's trajectory.

Although the method of redundancy resolution is well understood for local optimization using the Jacobian matrix (see, e.g., [19]), we try to expand the knowledge of redundant robot systems onto a global view on redundancy. Based on this goal, cost functions for any type of manipulators (e.g., mobile, serial) can be formulated and computed for the entire system. Moreover, a compliance control scheme should be developed which uses this extensive description of the kinematic behavior. In case of a higher number of freedoms in the system (more than one) a multi-priority control can be used in a meaningful way. Thus, the aim of this work package is to realize the computation of a primary task (given trajectory of the end effector), a compliance control of the whole robot system and a desired optimization (e.g., energy minimization) based on one mathematical concept.

5. Conclusion

In this article, the research project CollRob was presented proposing novel methods for human-robot collaboration. Research covers machine perception, sensitive redundant kinematic manipulation, dynamic adaptive planning, human-robot interaction and information exchange, human state evaluation, and safety. To integrate different methods and system components into one working setup, a software architecture has been developed based on a publish-subscribe principle implemented in ROS. Different use cases have been identified and will be addressed for evaluation purposes of the developed methods including a demo use case of joint human-robot Tangram puzzle building and various industrial applications in collaboration with company partners.

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