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Design of a Collaborative Architecture for Human-Robot Assembly Tasks

Ilias El Makrini^{1*}, Kelly Merckaert¹, Dirk Lefeber¹ and Bram Vanderborght¹

Abstract—Collaborative robots, the so-called cobots, that work together with the human, are becoming more and more popular in the industrial world. An example of an application where these robots are useful is the assembly task. In this case, the human and the robot complement each other. On one side, the human can achieve more dexterous tasks, while on the other side, the robot can assist the assembly process to lower the physical and cognitive work load, e.g. to avoid errors, and in the same way reduce absenteeism. This paper describes a novel collaborative architecture for human-robot assembly tasks. The developed architecture is composed of four modules; face recognition, gesture recognition and human-like robot behavior modules are used to enhance the human-robot interaction, while the visual inspection module is utilized for quality control during the assembly process. A collaborative task consisting of the assembly of a box whereby the robot assists the human was designed and implemented on the Baxter robot. This was used as the application use case to validate the developed collaborative architecture.

Index Terms—collaborative architecture, human-robot assembly, face recognition, gesture recognition, visual inspection

I. INTRODUCTION

NOWADAYS, industrial robots are heavy machines that are separated for safety reasons from human workers by cages [1]. They are programmed to work autonomously following a fixed program and to perform repetitive and heavy-duty tasks. Although these robots are often used in assembly lines, they have some limitations such as a lack on dexterity. Therefore, many assembly jobs are still performed by humans. In many cases, they have to work in non-ergonomic poses, which results in workplace injuries. Also, humans are more prone to errors, especially when the product variability is high.

Recently, there is a strong trend in both the research community and in the industry toward the development of collaborative robots, the so-called cobots [2]. Instead of being caged, they should work together with people in a cooperative environment to assist with complex tasks that cannot be fully automated and to fulfill tasks that could be risky for people, which results in fewer accidents on the work floor [3]. Combining the dexterity, flexibility and problem-solving ability of humans, with the strength, endurance and precision of robots [4], the quality of the industrial production can be improved, as well as the working conditions for humans [5]. Humans will not do any longer the dull and dangerous jobs,

and the amount of workplace injuries, e.g. musculoskeletal disorders that affects millions of workers worldwide each year and that costs businesses billions in revenue [6], will decrease.

In Cherubini et al. [7] the workload of the operator is reduced by the development of a human-robot manufacturing cell that can manage human-robot physical interaction and alternate between active and passive behaviors. To allow human-robot task allocation during collaborative assembly tasks, Tsarouchi et al. [8] proposed an intelligent decision-making method. In [9], a task allocation framework based on a hierarchical task decomposition is developed for human-robot collaborative assembly tasks. Roncone et al. [10] proposed a transparent task planner capable of allocating tasks and assigning roles. In [11], robots are put in charge of the quality control, more specifically, they are used in an assembly line to inspect the quality of the products assembled by the workers.

To achieve an efficient Human-Robot Collaboration (HRC), the starting point is to establish a good communication protocol among the human and the robot. This can be achieved either by explicit communication or implicitly by actions. Main ways of communicating ones intentions are speech, gestures (e.g. facial expressions, eye gaze, explicit hand and body gestures, manipulative gestures), actions (e.g. proactive task execution), and haptic signals [4]. Note that, due to the noisy industrial environment, communicating through speech is not always feasible, so gestures become more suited. Therefore, Gleeson et al. [12] proposed a gestural communication lexicon for human-robot collaboration in industrial assembly tasks, and in [13] an approach for recognizing pointing gestures for Human Robot Interaction (HRI) was developed.

Regardless of the communication method that is chosen, studies show that, in order to make the robot accepted by the user, the communication between human and robot has to be as much natural as possible [14], [15]. Therefore, it is important that the complexity of the communication is always hidden from the user. Zanchettin et Al [16] also showed that human-like motions of the robot might facilitate the social acceptance.

This paper presents a collaborative architecture that combines face recognition, gesture recognition and human-like robot behavior for enhanced human-robot interaction and visual inspection for quality control during human-robot collaborative assembly tasks. In the developed architecture, the robot's role consists in assisting and guiding the human

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during the assembly process. This is particularly useful when assembling complex parts made of multiple components or for parts with varying designs. This novel system is validated on the collaborative robot Baxter [17], whereby the robot assists the operator with the assembly of a box.

The paper is organized as follows. Section 2 gives an overview of the developed collaborative architecture along with the technical implementations. Section 3 presents the application use case, namely the collaborative assembly of a simple box. Section 4 describes the experimental validation. Section 5 ends the paper with some conclusions and future perspectives.



Fig. 1. The collaborative Baxter robot. A Kinect v2 camera is placed on top of the robot for gesture and face recognition. The camera is placed on the robot's head to avoid occlusions by the arms and the parts.

II. COLLABORATIVE ARCHITECTURE

In order to achieve a good human-robot collaboration, a good communication between human and robot is

required. Therefore, the robot is able to manage a number of social components such as gesture recognition and face recognition. The latter is used to personalize the robot for each operator, whereby the user is identified and greeted. On top of this, for a qualitative and correct production, especially for manufacturing in low quantities and high variability, it is needed to reduce apart from the physical load, also the cognitive load. One way to achieve this, is by offering the components of the assembly in the correct order and by performing afterwards the quality check.

The developed collaborative architecture is composed of four different modules: gesture recognition, face recognition, visual inspection, and human-like robot behavior.

A. Gesture recognition

Since noise is often present in factories, speech recognition is not possible. Therefore, gestures are used as an effective mean of communication to interact with the robot [14]. This allows the user to communicate with the robot via different kind of gestures such as waving, thumbs up/down, etc.

The gesture recognition is performed by a Kinect v2 camera placed on the robot head as shown in Fig. 1. The middleware NiTE 2.2 [18] is used to process the Kinect data. The latter utilizes the depth, color, IR and audio information of the camera to achieve hand locating and tracking, accurate user skeleton joint tracking and various gesture recognition. Two gestures are used in the collaborative assembly task: the hand waving and the thumbs up gesture. These are shown in Fig. 2.

B. Face recognition

The interaction with end-user companies revealed an important feature needed for collaborative robots, namely the ability to identify people. The reason behind this is to allow only dedicated users to interact with the robot.



(a) Waving

(b) Thumbs up

Fig. 2. Depth images during the gesture recognition with the Kinect v2 camera using the NiTE 2.2 interface. Two gestures are shown here: the waving and the thumbs up gestures.

Therefore, face recognition is used for user identification.

Face recognition is the first module of the collaborative architecture. It is performed via the Kinect v2 camera. The images are processed by the IAI Kinect2 ROS package [19]. The latter is a collection of tools and libraries for a ROS interface to the Kinect v2. The face detection algorithm is using the ProcRob ROS package [20] and is based on eigenfaces. This package provides a simple actionlib server and client for implementing face recognition. Fig. 3 shows the detected face of a user. Performing a face recognition allows to determine if the user is authorized to work with the robot. The acquired face can be compared to workers faces of a database.



Fig. 3. User recognized by the face recognition module during the identification process.

C. Visual inspection

An important aspect of the assembly lies in the quality control during the process. In case an error is detected at the end of the assembly, the partial or full disassembling of the part might be needed which leads to higher costs. The aforementioned situation becomes especially an issue for small volume productions with high variability. Therefore, it is important to perform an intermediate quality check during the assembly process. To ensure the quality of the assembly, two strategies are adopted. First, the process is guided by the robot, i.e. the parts are given in the correct order. Second, a quality control is carried out by the robot once a new part is assembled by the human.

During the implemented assembly task, the robot checks if the plate has been correctly screwed by the user. This is realized by a visual inspection of the assembled plate via the camera in the wrist of the Baxter robot. The inspection operation is shown in Fig. 4. The screws are detected by the object detection module. This is realized by determining the number of circular features in the images via a circle Hough transform provided by the OpenCV library [21]. By measuring the radius of the detected circle, it is possible to distinguish holes from screws. Fig. 5 shows the output of the visual inspection algorithm.



Fig. 4. Baxter checking the number of screws via the wrist camera during the assembly task.

D. Human-like robot behavior

This module controls the robot behavior by providing social cues such as head nodding/shaking and eye gaze. Studies showed that the presence of social cues increased the social acceptance and intention to work with collaborative robots [14].

1) *Eye gaze system:* In order to mimic the eye gaze of humans, an eye gaze system was implemented in the robot. Three different displays are used for this purpose (see Fig. 6). The gaze is directed to the end-effector of the moving robot arm. The eye-gaze system allows to communicate the intention of the robot to the user which increases safety and acceptance [14].

2) *Head motion system:* A head motion system was implemented, consisting of a head nod to indicate acceptance and a head shaking to indicate refusal. This is used in the collaborative assembly task to give a positive feedback when a thumbs-up, waving is recognized or a negative feedback during the visual inspection in case of missing screws. Such reactive feedback via the head motion is important in order to communicate to the user that the robot understood his intentions.

3) *Text display:* Several text displays have been programmed to communicate or request information from the user. Fig. 7 shows an example of three text display screens where the robot respectively greets the user, asks to start the demo and signals missing screws. The text displays can also be used to guide the user in the assembly process.

III. COLLABORATIVE ASSEMBLY

This section presents the application use case used to validate the collaborative architecture. It consists of a human-robot assembly demo of a simple box implemented in the Baxter robot. The robot is controlled under the Robot Operating System (ROS) framework.

The setup consists of the Baxter robot and a table where the parts are placed, as depicted in Fig. 1. The main parts of

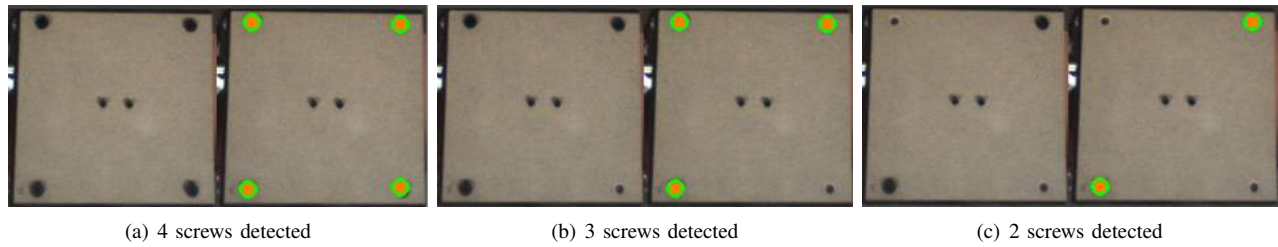


Fig. 5. Detection of the number of screws on the plate of the box assembled by the operator during the visual inspection procedure using the robot's wrist camera.

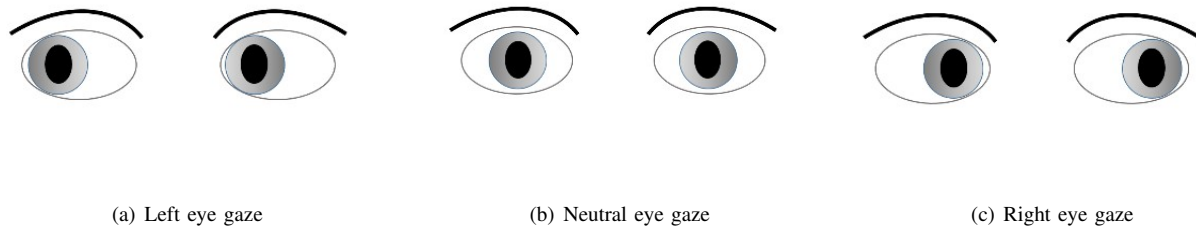


Fig. 6. Eye gaze system of the human-like robot behavior module implemented on the Baxter robot. From left to right: left eye gaze, neutral eye gaze, right eye gaze.

the box, namely the bottom and front plates, and the lid are shown in Fig. 8.

The bottom and front plates need to be screwed while the lid is attached to the box via two clips. Screws are also available on the table in two containing boxes along with a screwdriver. The semi-assembled box is placed on the left part of the table, as shown in Fig. 8.a. The box is built with laser cutted medium-density fiberboard (MDF) wood plates and 3D printed plastic attachments. Extra handles are also added on the plates to facilitates the picking of the parts by the robot. In order to make the manipulation of the screws easier, M5 screws are used.

The robot guides the assembly by holding and handing the appropriate part. The human task consists in assembling the plate correctly on the semi-assembled box by screwing them.

The assembly process consists in:

- Holding the semi-assembled box in the appropriate orientation (robot)
- Picking the appropriate plate (robot)
- Handing the plate to the human (robot)
- Handing the screws and screwdriver if necessary (robot)
- Positioning correctly the plate on the semi-assembled-box (human)
- Screwing or attaching the plate (human)
- Checking quality of the assembly (robot)

Fig. 9 shows several pictures during the assembly process. Fig. 9.a depicts the robot holding the semi-assembled box at the appropriate orientation for the assembly of the bottom plate. Fig. 9.b and 9.c show respectively the handing of the plate and the screws. The screwing operation is shown in Fig.

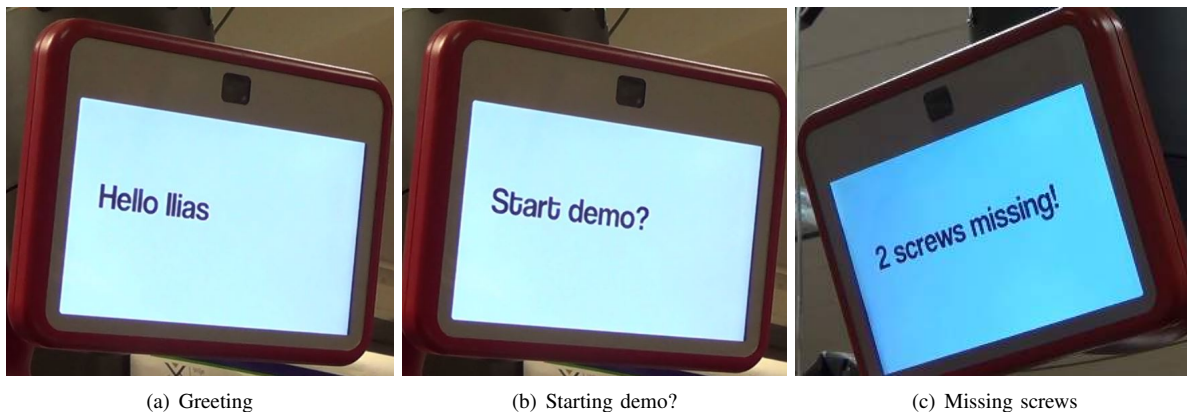


Fig. 7. Set of implemented text communications. From left to right: greeting the user, asking information ("Starting demo?") and giving information ("2 screws missing!").

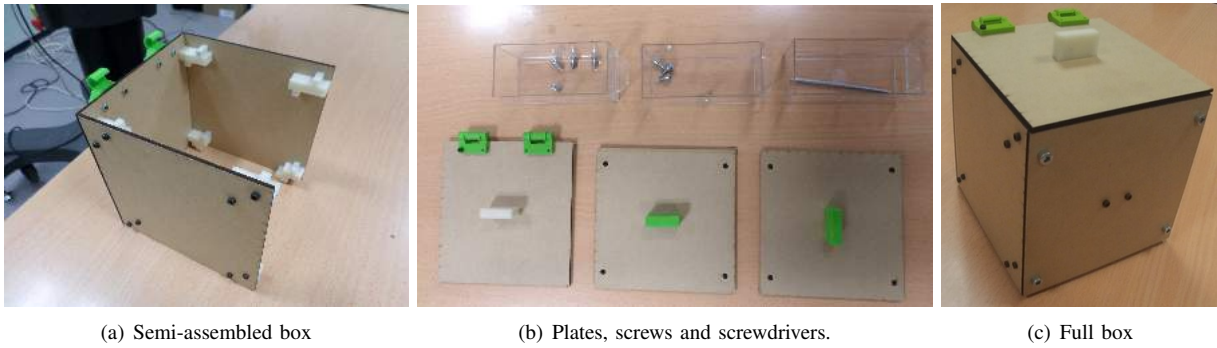


Fig. 8. Full box and dismantled parts to be assembled placed on the table in front of the robot. In the right picture, the left plate (lid) is attached to the box via hinges while the two other plates (bottom and front of the box) are attached via screws.

9.d.

IV. EXPERIMENTAL VALIDATION

The implementation of the collaborative architecture for the human-robot assembly task is represented by the flowchart of Fig. 10.

First, the gesture recognition module is started. If a hand waving is detected, the human-like robot behavior module sends a feedback to the human in the form of a head nod. The face recognition procedure is then launched. The detected face is compared with faces of allowed users in a database. If the face is recognized, a text feedback is displayed on the robot's display: "Hello + user's name". The robot asks then the user if the assembly can start. By making a thumbs-up gesture, the assembly process is launched. In the meantime, the robot confirms that the gesture was detected via a head nod. Baxter picks then the appropriate parts and hold or hand them to the user. In function of the process task, either "Part grabbed?" or "Part assembled?" is displayed on the robot's head. Once a plate is assembled and after the detection of a thumbs up gesture, the visual inspection procedure starts. A picture of the assembled plate is taken via the robot's wrist camera. The algorithm detects then the number of screws. If four screws are detected, the part is correctly assembled. Otherwise, a negative feedback is given to the user by shaking the head of the robot. The number of missing screws is also displayed on Baxter's face: "X missing screws!" and the user is asked to re-perform the screwing. Once the plate

is correctly assembled, the robot can move on to the next task of the assembly process until completion.

V. CONCLUSION AND FUTURE WORK

We have described a novel collaborative architecture for human-robot assembly tasks. The architecture was validated on a collaborative task where the robot assists the human in a box assembly. Thanks to the gesture recognition, the human can communicate with the robot during the assembly process. The face recognition module allows to identify the user and provide a personal experience. During the process, the robot performs intermediate quality checks via the visual inspection module. Finally, thanks to the social cues of the human-like robot behavior module, a more intuitive human-robot interaction is achieved.

Other features could be added to the existing architecture to improve the human-robot collaboration. An example of such improvements is the adaptation of the robot behavior to the user, e.g. the speed and the height at which the parts are given. Based on the returned information of the face recognition module, the height of the person can be extracted. This can be used to adjust the position of the parts when handed or hold by the robot.

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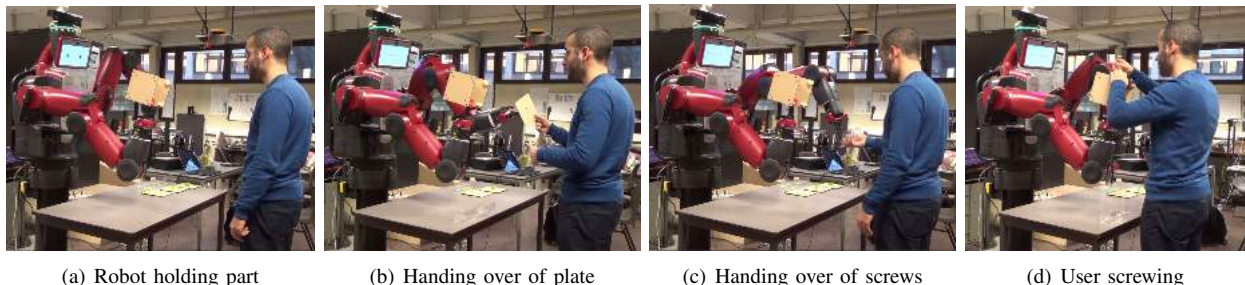


Fig. 9. Pictures of the collaborative assembly task. In chronological order, the robot is holding the semi-assembled box, handing the plate, the screws to the user and the screwing performed by the operator. Link: <https://youtu.be/0azX0cJgWRc>

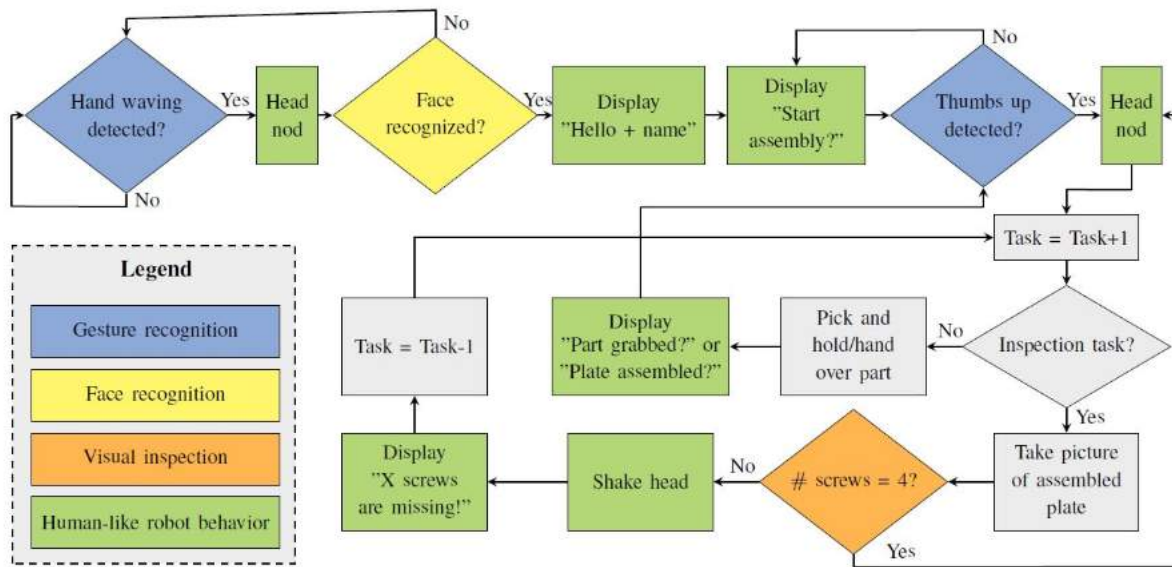


Fig. 10. Flowchart of the human-robot assembly task with blocks associated to each module of the collaborative architecture, namely the gesture recognition, the face recognition, the visual inspection and the human-like robot behavior modules.

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