Working with Walt: How a Cobot Was Developed and Inserted on an Auto Assembly Line

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ClaXon: Study and Implementation of Robotic Coworkers in an Industrial Context

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***Abstract*— Collaborative robots or co-bots are a category of robots that are designed to work together with humans. By combining the strength of the robot such as precision and strength with the dexterity and problem-solving ability of the human, it is possible to achieve tasks that cannot be fully automated and improve the production quality and working conditions of workers. This paper presents the results of the ClaXon project which aims to study and implement interactions between humans and collaborative robots in factories. The project has led to the integration of a co-bot in the car manufacturing production plant of Audi Brussels in Belgium.**
Proofs of concepts were realized to study multimodal perceptions for human-robot interaction. The project addressed technical challenges regarding the introduction of collaborative robots on the factory floor. Social experiments were conducted with factory workers to assess the social acceptance of co-bots and study the interactions between the human and the robot.

***Index Terms*— collaborative robots, social human-robot interaction, computer vision, sensor fusion**

I. INTRODUCTION

Collaborative robots, also called co-bots or coworkers, are starting to be introduced in the industrial world [21]. Such coworkers, unlike classical industrial robots which are separated from workers by cages, break down the human-robot barrier to offer a more flexible and affordable solution for manufacturing companies. By combining the complementary strengths of the human, i.e. dexterity and problem-solving ability, and the robot, i.e. strength and precision, the integration of tasks that cannot be fully automated becomes possible while the production quality and the working conditions of human workers can be improved [6, 16].

Audi Brussels, a car factory in Belgium, is such a company where the potential of collaborative robots can improve the productivity of the manufacturing process. To produce the Audi A1 car, the factory employs a total of 550 industrial robots in the body shop and 30 robots in the paint shop. The number of robots in the assembly line is lower; only 6 industrial manipulators are employed. The limited automation for the assembly process is due to several reasons. First, the products have a higher variability. This is induced by the different possible customizations of the produced cars. Second, the used materials have a higher sensitivity. Third, compared to other processes, the product assembly process is more complex, making the automation more challenging.

Another challenge faced by the company, and which is one of the current societal challenges, is the aging of the workforce. The introduction of collaborative robots in factories to assist workers could help in reducing the workload and workplace injuries such as musculoskeletal disorders [20].

In recent years, several technologies have been created for a better human-robot collaboration such as actuators [11], sensors [9] and control algorithms [5]. Extensive research has also been carried out on the task distribution between the human and the robot. Roncone et al. [22] developed a transparent task planner for role assignment and task allocation. Although several technical advances have been realized in labs to enhance human-robot collaboration, there is a lack of knowledge about the implementation and the acceptance of collaborative robots in real industrial context, which is essential to guide future research.

Regarding social acceptance studies, current research in the industrial environment is limited (e.g. [23, 26]) and is often realized in laboratories or with students. The current challenge is to involve people working in the manufacturing domain, bring in their daily knowledge and investigate with them the opportunities of human-robot collaboration in their environment. Such studies [23], [26], however, are important since they report how workers experience working with robots and how collaborative robots or the collaborative process could be improved. Wurhofer et al. [26] conducted a study in which workers of a semiconductor factory were interviewed about their experiences with robots over time. The results suggested that their work experience was affected in different ways. For example, the workers had different expectations from the robot. They also had to adapt their own work process to the robot. Furthermore, Sauppé and Mutlu [23] found that workers in their study established social relationships with the Baxter robot (Rethink Robotics). They suggested that sociality is very important for robots, but they also suggest that the robot's design should match the robot's safety since more sociality could create a false sense of safety.

This paper presents the results of the ClaXon project, a project aiming at improving the interaction between people and collaborative robots in factories. During the project, two main challenges were addressed: first, the development of tools to enhance the flexibility of co-bot systems through learning strategies using multimodal input; second, the introduction of a co-bot on the factory floor. Aside from the technical advances, social studies were realized to assess and improve the acceptance of co-bots. The project has resulted in several proofs of concepts demonstrating future capabilities of human-robot collaboration in an industrial context as well as the implementation of a fully operational co-bot at the Audi Brussels production plant. This allowed unique insights throughout the full process of implementing a collaborative robot in a real factory setting, while much (social) research in this domain is restricted to lab settings. It should be mentioned that, due to the lack of local safety regulation in Belgium, the co-bot system at Audi was designed such that direct interactions with the robot is limited. The developed system represents, however, a first step forward in human-robot collaboration.

The project consisted of two phases. First, social requirements for human-robot interaction were identified (Section II) along with technically possible solutions for HRI (Section III). During this preparation phase, the Baxter robot was used as a research platform. In a second phase, the information collected in the first phase was utilized to select a use case. The use case at Audi Brussels was addressed by a collaborative robot Kuka KR 5 SI, which was successfully implemented on the actual manufacturing line of the Audi A1 (Section IV). The solution benefitted from knowledge gained from the different research tracks in the project. Social acceptance studies were also conducted with factory workers.

II. Socially Desirable Human-Robot Interaction

During the first phase of the project, social requirements were investigated for a desirable human-robot interaction, i.e. that leads to a higher acceptance of the robot.

A. Related work

The adoption of collaborative robots could help with the challenge of the aging workforce by reducing the workload for factory workers. Moreover, our research has suggested that factory workers acknowledge this advantage [6]. However, at the same time, we learned that they feared job loss due to the introduction of even more robots (cf. [26]). This fear could be hindering the (social) acceptance of working with such robots.

There is a limited but growing amount of research focusing on experiences of factory workers collaborating with co-bots outside the lab (e.g. [23]). We contributed by conducting both qualitative and quantitative research in a real factory environment with real workers [6, 7].

B. Social studies

To study the attitudes of car factory employees, we conducted a survey among 42 of them, in which we asked several questions from the Eurobarometer 427 questionnaire on Autonomous systems including robots [8]. 74% of our respondents conducted manual labor, 21% white-collar workers and 5% other. 84% of the respondents indicated to be fairly (63%) to very positive (21%) about robots, while 13% considered themselves to be fairly negative and 3% very negative. To the question "*Do you think your current job could be done by a robot in the future?"* 5% indicated entirely, 21% mostly, 32% partially and 42% not at all.

An open question was asked about the perceived advantages and disadvantages of robots.
Perceived advantages. 29% of the respondents answered *less strenuous work*, a *higher production speed* (20%) and *a higher production quality* (14%). Other perceived advantages included *reliability* (11%), *that a robot can be programmed* (6%) and no advantages (3%).
Perceived disadvantages. *Less jobs* and *no concerns* were indicated most frequently (23%). Other concerns included *breakdowns* and *safety* (both 13%) and *replacing the job of workers* (10%).

Social experiments were conducted at Audi Brussels with factory workers to investigate the human-robot interaction using gestures and evaluate the importance of social cues [7]. A pick-and-place task was programmed on the collaborative robot Baxter using the Wizard-Of-Oz method. In other words, the gesture recognition was done by one of the researchers and he operated Baxter via his laptop. The operator's task consisted in instructing the robot via a set of gestures (thumbs up/down, 1/2/3 fingers, swipe left/right) the quantity of parts and the brick type (red, blue, white, yellow) that the robot needed to pick and place in a box (left/right) as shown in Fig. 1.

The task was programmed with two conditions: one condition with social cues such as head nodding, eyes, and head gaze; and the second condition without social cues. Elprama et al. [7] concluded that the condition with more social cues increased the perceived enjoyment and the intention to work with co-bots (social acceptance). In other words, the factory workers were more willing to accept working with the robot and enjoyed this more when the robot's head nodded, when it showed eyes on the display and when the head was following the arm movements of the robot compared to not making all these movements.

Additionally, three recommendations were identified in [6] to improve further collaboration, 1) the co-bot should be able to adjust its height to that of the worker to facilitate collaboration, 2) the co-bot should be able to adjust to the language spoken by the operator it is collaborating with, 3) that the co-bot should adapt itself to the desired working speed of the workers as this is not possible with the industrial robots. By getting input from the users, it is possible to design better co-bots that meet the needs of the workers and by doing so encourage acceptance and use of robots.

Fig. 1: Social experiments where the Baxter robot is used to investigate gestures and social cues.

III. Human-robot Interaction through Multimodal Perception

During the first phase of the project, multimodal perception was investigated for an intuitive human-robot interaction along with the related tools to set up such interactions.

A. Related work

Currently, the interaction between robot and machine is mainly done over buttons or graphical user interfaces and only controllable by trained skilled persons. The trend is that the interaction becomes multimodal and human-centered so that complex and well performing robots can be safely controlled "intuitively" using human-like communication cues. In noisy industrial conditions, reliable verbal communication is difficult for humans and impractical for machines. Therefore, efforts on gestural expression and recognition are on-going [10, 19]. Moreover, taking into account the human's intention and preferences, the robot will be enabled to interact socially and realize a human-friendly and interactive behavior [12].

In order to handle input from multiple input sources in multimodal interaction, a typical multimodal system first uses specific components to interpret the measurements from a single modality (or sensor), also called input recognizers, this information is then later combined in a fusion engine, which combines the results of the recognizers. This fusion engine recognizes the human's request (intent or intended interaction), which is then handled by a dialog manager that determines the appropriate reaction given the system's state and knowledge sources. A last component, the fission engine, then determines the appropriate way to convey this reaction to the human [1].

Several approaches [18, 2, 4] have been proposed to steer the behavior of the fusion engine, dialog manager and fission component that together determine which reaction will be given to detected input.

B. Domain-specific language

To prototype the multimodal interaction for proof of concept collaborative setups, we used a domain-specific language that combines state machines with a compact textual language. This language [2] was chosen as an experimental evaluation showed that it offers both low-level control over interaction techniques as well as high-level control over the overall human-robot collaboration. Furthermore, an experiment demonstrated that, for a specific task, participants were significantly faster to adapt a multimodal interaction specification with the domain-specific language than with a familiar general-purpose language [2]. In contrast to several other HRI approaches [17] [24], it is also not centred around voice-based interaction.

This language and the supporting tool were used to discuss the interaction, implement and test alternative gestures (hand pose detection through a SoftKinetic DS325 depth camera and related CILib SDK) to give the commands in combination with different sensors (sonar, RGB video with face detection and recognition) to identify and locate people near the robot [25]. Fig. 2 shows the execution of such gesture-based interactions with the Baxter robot. The gesture recognition is performed by the Time-of-Flight SoftKinetic camera DS325. Features are extracted from the 3D point-cloud and mapped to static gestures. We conducted an evaluation of the language to investigate whether different stakeholders (including engineers, robot programmers and PLC programmers, all employees of the industrial partners in the ClaXon project) would be able to understand the language and make adaptations to existing specifications. The experiment started with a short introduction to the language, followed by 7 multiple choice questions. Participants had to rate how easy it was to answer (1-7) these questions and could give a motivation. Each experiment ended with a short discussion about the language.

Fig. 2: Proof of concept using the Baxter robot for multimodal interactions (gestures and face recognition).

9 out of 17 participants made no mistake, 4 made 1 mistake and the others gave two wrong answers. An analysis of the results showed that all 17 participants could understand simple specifications and indicated some guidelines for more complex specifications to maximize comprehensibility. For all questions, 11 or more participants gave an ease rating of 4 or above (higher is easier). We noticed that the 3 PLC programmers without other programming experience rated the questions as being difficult. Some limitations of the language with respect to viscosity (resistance to change) and diffuseness (number of symbols for one meaning) were identified. These are addressed in DICE-R [15].

IV. From Research to Industry

In this second phase of the project, the information collected in the first phase were used to design the human-robot interaction of a co-bot implemented at the Audi production plant. These include the social cues identified during the social experiments as well as the technical solutions for multimodal human-robot interaction (gesture and face recognition).

A. Use case

The use case at Audi Brussels focuses on applying glue to reinforcement plates (see Fig. 3). These are used to support the car's roof racks. The worker's job consisted of picking the reinforcement plates from a container and stacking them on a small table. By using a glue pistol, the operator would apply two stripes of glue on top of the metal plates. The worker would then attach the appropriate reinforcement plates to the side panel of a two-door or a four-door car from two parallel assembly lines.

Fig 3: Example of a manually glued reinforcement plate. The applied glue stripes are not uniformly distributed along the plate.

The drawback of this whole process lies in the gluing. Since this is was done manually, the quality was not optimal, i.e. the glue was not uniformly distributed along the plate. It was also dependent on the skills of the person performing the gluing task and other factors such as temperature and time of the day. This was affecting the quality of the produced car. In this case, the use of a collaborative robot (high precision) enables a better product quality while taking over the repetitive and dirty tasks of the human worker. This use case is also used as an example to demonstrate the technologies developed throughout the Claxon project.

B. Co-bot Walt

The ClaXon project led to the integration of a collaborative robot, "Walt", in the Audi Brussels production plant. Fig. 4 shows the developed MRK-Systeme robot along with the interaction with factory workers. "Walt" works in close proximity to humans and does not need a safety fence. An actuated robotic head was developed by Robovision to express emotions for human-robot communication. Relevant social cues identified during the social experiments were implemented such as eyes and head nodding and shaking.

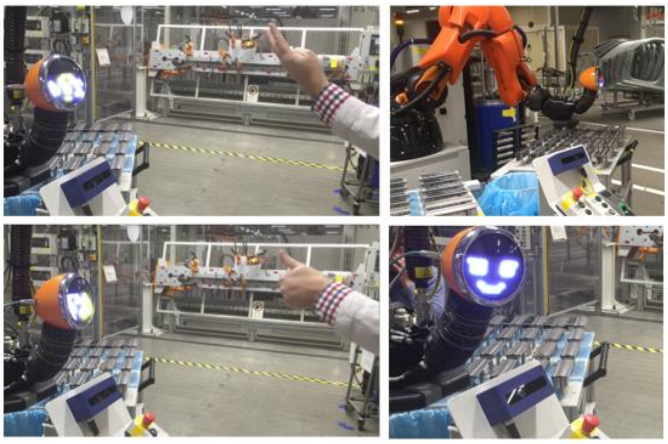

Fig. 4: Collaborative robot "Walt" at the Audi Brussels factory. The interaction with the robot is performed with gestures. An actuated robotic head is used to communicate with the worker and express emotions. More details can be seen in the video available at https://vimeo.com/210892103

C. Gesture-based interaction

Due to the noisy environment in the factory, gestures were used to communicate with the robot. The operator instructs "Walt" with the following gestures: pointing left/right to indicate the assembly line, 2/4 fingers to tell the robot which parts need to be glued (2/4 doors car-parts) and thumbs up/down to confirm or disconfirm the action. These are shown in Fig. 5. Static gestures have been preferred over dynamic gestures (e.g. hand swiping gesture). Indeed, it has been observed during the social experiments that static gestures are easier to detect and lead to the most consistent performance. This specific set of gestures was selected since these are similar to non-verbal human-to-human communication gestures used in the factory.

Fig. 5: Gestures used for human-robot communication with the "Walt" robot.

D. Gesture recognition

The gesture recognition is performed by a RoboSense camera (Robovision brand) that integrates a structured-light camera (3D, 640x480), an RGB camera (1280x1024) and an embedded processing unit (ARM cortex, octa-core). The recognition method is based on the Histogram of Oriented Gradients (HOG) feature descriptor [3]. First, a threshold is applied to the depth data provided by the 3D camera to separate the foreground, composed of the user's hand, from the background. A window is determined around the hand. The extracted image using the latter window is then split into cells for which the gradient magnitude and direction is calculated for every pixel. This information is combined into a histogram of oriented gradients. The HOG features of the cells are concatenated to obtain a feature vector of the entire image. This vector is used as the input of a classification algorithm based on a multi-layer-perceptron neural network.

E. Face recognition

Face recognition was also integrated to recognize the operator. A deep learning approach was implemented using RGB images collected during the registration phase of the worker in the database. ResNet [13] neural networks with 29 convolutional layers were used to learn workers' face. Operator's identification was reinforced with fingerprinting scanning using a ZKteco F18 scanner. This is realized once a day per person and allows to check if the worker is authorized to work with the robot.

F. Glue and part detection

In order to give the robot a visual feedback during the gluing process, RoboSense cameras were integrated with the setup to detect the reinforcement plates on a rack. These cameras are mounted on an unactuated beam that moves loosely together with the robot to prevent robot collisions. Therefore, this intelligent camera system was not only used for parts and glue detection but also to find the rack that holds the parts, independent of its position and pose. Object detection is performed by segmentation using 3D images and heuristics to find the table pattern formed by the placeholders of the parts. First, a threshold is applied to the depth image provided by the structured-light camera to identify the metal parts. These are located at the same height above the table. Fig. 6 shows the camera view along with the obtained segmented depth image. The latter is mapped to the 2D image of the RGB camera to extract image patches for every reinforcement plate. A color filter is applied to accentuate the black color of the glue and attenuate the other colors. The images are sent to a classification algorithm based on a convolutional neural network that determines if glue is present on the parts.

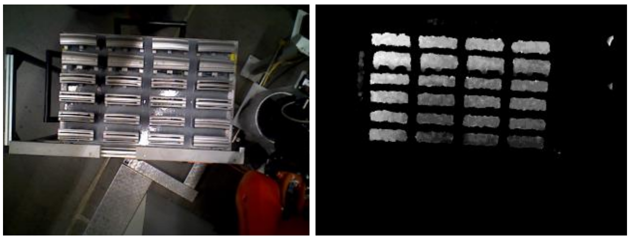

Fig. 6: Camera view (left) and segmented depth image (right) of the glued reinforcement plates. White pixels represent near points and dark pixels represent distant point.

G. Safety

In order to achieve a safe interaction, the Kuka KR 5 SI robot implemented by MRK-Systeme was utilized for the gluing process at Audi. It must be noted that although different robots were suitable for the use case such as the Kuka lightweight robot or the Universal Robots UR5 we were limited to the KR 5 SI (SafeInteraction) from MRK-Systeme since this was the only robot, during the project preparatory phase, certified by the Berufsgenossenschaft Holz und Metall (professional association wood and metal). Therefore, this was the unique allowed robot for safe human-robot interaction on the Audi manufacturing floor.

Fig. 7 shows the MRK-Systeme robot performing gluing of the reinforcement plates in the factory of Audi Brussels. The MRK-Systeme robot is a suitable platform since it can operate without separating safeguarding equipment. Safety is based on various functional mechanisms. The work envelope and speed of the robot are controlled according to the safety requirements of the standard DIN EN ISO 10218-1 [14] such that the applied forces stay below the biomechanical limits. Also integrated cushioning elements are used to reduce the contact forces. The robot stops in case of collisions with humans. These are detected by a safety skin as shown in Fig. 7. The glue gun, which is a potentially hazardous part due to its point-shape, at the end-effector is framed by a plastic case so the required safety level is achieved.

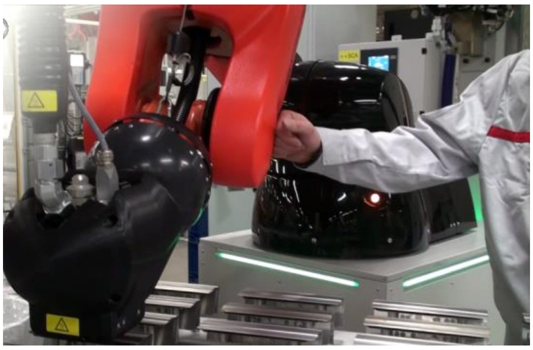

Fig. 7: MRK-Systeme robot during the gluing process. The safety skin of the robot detects human contacts. The end-effector is framed by a plastic case.

H. Improved quality

The integration of the collaborative robot "Walt" allowed improving the quality of the produced cars. The gluing quality of the reinforcement plates of the assembled car is determined according to flatness measures. It has been observed that the number of cars that do not fulfill the flatness criterion has decreased by 15%. Moreover, the total quantity of glue used during the process, i.e. quantity used for a determined number of cars, has decreased by 20%.

I. Fool-proof design

The co-bot system has been designed to reduce as much as possible undesired faults and uses robust technologies. For instance, for gesture recognition, a confirmation with a thumbs-up is required to validate the command gesture. In the case of a robot misinterpretation, the operator can disconfirm the command with a fist gesture, as shown in Fig. 5. Moreover, in order to reduce missuses for new operators, information regarding the robot usage is displayed in the factory. Markers are also placed on the floor to indicate the interaction zone. During the operating service, the robot works in collaboration with two workers, one at a time.

J. Operator role

The operator performs tasks that are difficult to automate. In this case, its job consists in picking up randomly placed metal reinforcement plates from a bin. These are then disposed on a cart placed in front of the robot. Another situation where the operator's intervention is needed concerns tasks that require the knowledge of the overall process. Here, the car type on the assembly line dynamically changes. Therefore, the worker needs to exchange messages with the robot in order to inform him about the plates that need to be glued. Gestures are used to indicate the current car type on the assembly line. For instance, a 2-finger gesture confirmed by a thumbs-up is performed by the operator to instruct the robot to glue metal parts corresponding to the 2-door car type.

K. Acceptance by operators

In terms of social acceptance of the robot, the interviews performed at the end of the project with the operators using "Walt" demonstrated that the robot had been accepted as part of the team. The robot would be a point of discussion and also of mockery by the operators. Furthermore, it was mentioned that working with the latest technology gave them a sense of pride. It was a topic that they would even gladly discuss at home and with friends [8].

V. Discussion and Outlook

The Claxon project has investigated social and technological aspects of co-bots in manufacturing industry in terms of human-robot interaction and robot-product interaction. Throughout the project, several tools were developed that allow faster and more flexible introduction of industrial and collaborative robots and the demonstration of complex robot behavior.
In order to assess the social acceptance of the technologies developed during the project, experimental studies were performed with factory workers to study the human-robot interaction and evaluate the importance of social cues.

The project's research results have led to the integration of a collaborative robot for the gluing process of car reinforcement plates in the manufacturing production plant of Audi Brussels.

While a successful collaborative robot was implemented for a real industrial application, it should be noted that the use case of Audi corresponds more to a human-robot cooperation rather than a real human-robot collaboration application that implies, for instance, direct interactions with the robot. This is due to regulations regarding safety. Although some new standards are developed in the context of human-robot collaboration, they are not yet enforced and therefore required by the regulators in order to define the liabilities. In Belgium, there is still no clear guideline/standard for safety inspection organs. As a result, the robotic systems are designed such that direct human-robot interaction is limited in order to prevent unforeseen situations for which the manufacturer can be held liable.

We believe that, in the future, a more dynamical approach to human-robot interaction should be taken which is not driven by legislation, but rather by the experience of end users supported by technological advancements. The use of co-bots is getting traction for applications within Small and Medium-sized Enterprises (SMEs), where expensive safety measures and cages are too big of an investment. However, as soon as the applicability of co-bots in our daily tasks becomes more apparent, co-bot manufacturers will be forced to give priority on advances in end-user requirements and technology; and drive legislation towards a clear and an acceptable set of safety regulations.

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