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A Skill-based Robot Co-worker for Industrial Maintenance Tasks

Paul J. Koch[a], Marike K. van Amstel[a], Patrycja Dębska[a], Moritz A. Thormann[a], Adrian J. Tetzlaff[a], Simon Bøgh[b] and Dimitrios Chrysostomou[b]*

[a]*Dept. of Mechanical and Manufacturing Engineering, Aalborg University, Fibigerstræde 16, Aalborg Øst, DK-9220, Denmark*
[b]*Robotics & Automation Group, Dept. of Mechanical and Manufacturing Engineering, Aalborg University, Fibigerstræde 16, Aalborg Øst, DK-9220, Denmark*

Abstract

This paper investigates the concept of a sensor based robot co-worker working in flexible industrial environments together with and alongside human operators. In this particular work, a realisation of a robot co-worker scenario is developed in order to demonstrate the implementation of a robot co-worker from the starting point of an autonomous industrial mobile manipulator. The cobot is applied on the industrially relevant task of screwing by the use of a skill-based approach. The technical work on the human-robot interface and the screwing skill is described.

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Keywords: Collaborative Robot; Skill-based Programing; Maintenance Task; Screwing Operation; Intelligent Manufacturing; Industry 4.0.

1. Introduction

The field of production is continuously developing and seeking new means and strategies for faster, more affordable, and flexible automation. Over the last years, the fourth industrial revolution has been responsible for

* Corresponding author. Tel.: +45 21 18 19 18
E-mail address: dimi@m-tech.aau.dk

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introducing novel ideas and establishing concepts that shape the smart factory of the future [1]. One of the pillars for flexible automation in the Industry 4.0 era is the integration of the collaborative robots. The concept of collaborative robots introduces new fields of application for industrial robots and allows them to work in close proximity with humans.

1.1. The field of collaborative Robots

The field of collaborative robots has been widely investigated, however, it has yet to be exclusively defined what type of robot can be specified as a collaborative one. Even with a multitude of products currently available [2, 3] and after the completion of many research projects [4, 5], the definition of a collaborative robot remains unclear.

According to SICK Sensor Intelligence the interaction between human and robot can be classified as one of three. “Coexistence" is the lowest level of interaction, where the human and the robot work together to carry out a process but does not share the workspace and work pieces are transferred between the workspaces. The second level is “cooperation”; the workspace is shared but is rarely used or entered concurrently and the robot and the human are not executing operations in the workspace simultaneously. The last and highest level is “collaboration”, in which the workspace is shared and both parties can carry out operations simultaneously [6].

The authors of this paper accept as the most precise the definitions provided by the German Institute of Occupational Safety [7] and the Technical Specification ISO/TS 15066:2016 [8]. According to the former, cobots are defined as: "*Collaborative industrial robots are complex machines which work hand in hand with human beings. In a shared work process, they support and relieve the human operator*". Furthermore, the Technical Specification states that a collaborative robot per definition shares a workspace. This requires an industrial manipulator, which is able to work safely and without endangering or injuring the human operator. Robots designed for this purpose, utilise force/torque feedback in their joints in order to stop their operation when collision occurs and they are often designed with rounded edges to minimise damage in case of potential collision. Typical examples of such design and technical considerations are the UR3 and LBR iiwa 7 R800 from Universal robots and KUKA respectively.

However, the definition above is not an exclusive definition, and in earlier works cobots have been classified differently [9, 10]. Using the classification by SICK this work strives to develop a system for safe human-robot collaboration. Safe interaction between a human and a robot derives from the need for more efficient, flexible and productive industrial cells, as well as for reduction of heavy workload and occupational stress for the human operator. This can be achieved by simplifying the execution of the robot’s tasks in the manufacturing industry, under human guidance [11].

1.2. Human-Robot Interaction

As an ideal case one should consider the case where a human and a robot are working continuously and coherently on one or more work pieces. The human operator is working alongside the robot sharing the workspace as well as the necessary operations while both seemingly intuitively recognise and adapt to the movements and operations of each other enabling mutual support. This collaboration would be of great value for improvement of manual labour that is difficult, unhealthy or disadvantageous to automate entirely.

In order to enable such advanced collaboration between a human and a cobot two technical aspects are essential. The first being sensor inputs enabling the robot to recognise and adapt to the presence of the human, and the second being a human robot interface enabling easy communication between the two parties. In relation to sensor inputs, the presence of force/torque sensors alone in the manipulator is inadequate. Other types of sensors such as depth/distance sensors and thermal cameras able to monitor the working environment are necessary. The second aspect can be addressed using means such as sound, visual instructions, voice control, or an intuitive graphical user interface (GUI). The latter is considered in this work as one of the key technologies in relation to collaborative robots. Also, the need of an intuitive human-robot interface is emphasised by the fact that cobots most likely will be applied in working areas of shop floor workers with none or sparse insight into how such robots operate.

Researchers have already been investigating ways to enable robot novice shop floor workers to handle and program robots. In literature, several examples of “learning from demonstration” approaches for programming can be found [12, 13, 14]. Additionally, similar method is used in the teaching phase in the Skill-Based System developed by Aalborg University, Denmark [15] while connectionless methods for operating the robot, such as body gestures, are becoming popular [16, 17]. The common scope of these methods is to achieve easy interaction with high usability, even for unskilled operators.

1.3. The Focus of the Work

The work described in this paper strives to develop a collaborative robot from the starting point of a mobile manipulator and focuses on creating a human-robot interface with intuitive interaction not only in the programming phase but also during the general operation of the robot. For the latter, an interface is implemented, which eliminates the informational distance between the working environment, the task at hand, and the user interface. Lastly, the developed system was applied to solve a screwing task in collaboration with a human operator via the use of a skill-based approach and communication through the designed human-robot interface. The main contributions of this paper are:

- A framework for how a mobile manipulator can be applied as a cobot.
- An intuitive Human-Robot Interface for teaching and execution.
- Conduction of screwing task in a skill-based manner while keeping the human in the loop.

2. Scenario and Methodology

At production facilities, where injection moulds are used, the maintenance process is crucial to ensure high quality. Until now humans working on the maintenance task have done this work manually. They are responsible for disassembling the mould, cleaning, performing inspections, detecting failures and repairing them. Screwing is a natural part of the maintenance process. In the era of intelligent manufacturing the human operators can perform these tasks while they collaborate with flexible robots.

2.1. The Hardware

To build a system capable of performing the described task special hardware and software was needed. As a main tool the Little Helper 3 was used. It was designed and created as a research project at Aalborg University in Denmark. The Little Helper is an assembly of 4 subcomponents: mobile platform, industrial manipulator, end-effector, and sensors [19] (Fig.1).

1. Neobotix MP-L655 mobile platform is equipped with on-board scanners (laser-range, ultrasonic and motor encoders) providing the robot with mobility and flexibility. Additional 4 omnidirectional wheels make the robot easy to move and place anywhere. The platform contains a battery pack, consisting of eight 12VDC lead acid batteries and an on-board computer with a 2.0 GHz dual core and 2 Gb RAM computer running Windows XP. It weighs 150 kg, has a payload of 100 kg, and a speed less than 1 m/s.
2. The robot manipulator is a KUKA LWR IV+. It has in total 7 axes, providing a great number of configurations, thereby making it extremely manoeuvrable. The payload of the robot is 7 kg, its weight 16 kg, and its speed with rated payload vary from 110 to 204°/s depending on the axis [20].
3. Auxiliary: The robot is equipped with torque sensors with maximum torque up to 176 Nm in some axes, helping to solve the task, which requires force feedback. As an end-effector a Schunk WSG50 2-finger parallel electric gripper was used. It has a maximum stroke of 110 mm, a maximum grasping force of 120 N, and a maximum speed of 420 mm/s [21].

2.2. The Software

The robot hardware is programmed and controlled by a software system called Skill Based System (SBS). The system runs based on ROS [22] and provides a neat and accessible way to interact with and program the robot. In the SBS the skills work as follows; as an input chosen parameters are taken along with the current state of the robot;

then the preconditions are checked in order to ensure that it is possible to execute the task with the set parameters. If the check is successfully finished the skill is executed. When the task is completed, the post conditions are checked to verify whether the task was executed correctly. As an output of this execution we get another state of the robot (Fig. 3). The SBS is structured in the following way; the operator can execute a task, which consists of smaller pre-defined blocks called skills, Fig.2. For example, to execute 'place the object into the box' task, 'pick' and 'place' skills are used. The SBS uses the approach of object-oriented programming, where each type of skill is a class. Each skill class is a child of a fundamental class, the "Base Skill", from which its variables and functions are inherited.

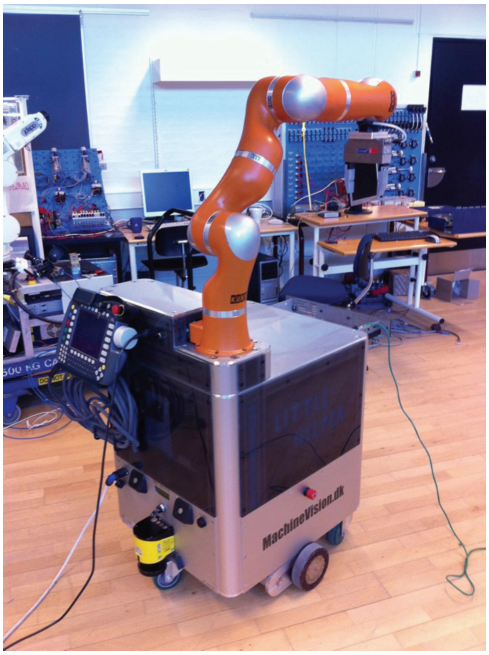

Fig. 1. KUKA LWR IV+ manipulator as part of Little Helper 3 [1].

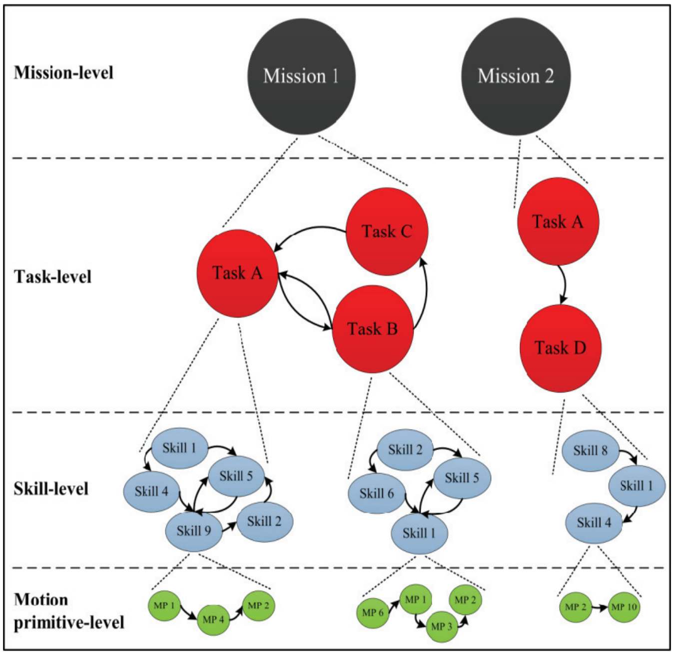

Fig. 2. An overview of the structure of SBS [18].

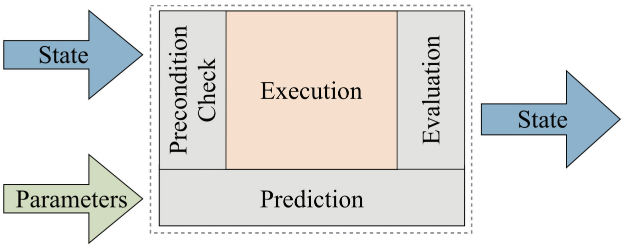

Fig. 3. The fundamental skill model used in SBS [15].

The SBS is implemented with a simple and intuitive Graphical User Interface (GUI). The main idea behind the SBS is that unskilled workers should be able to operate the system without special insight or extensive training. The robot can be controlled directly and moved around through the interface or it can be made freely movable. The GUI contains simple menus to support the operator in the decision making process by providing only the relevant information. The human operator is able to execute previously programmed tasks or to create new tasks using available skills (Fig. 4).

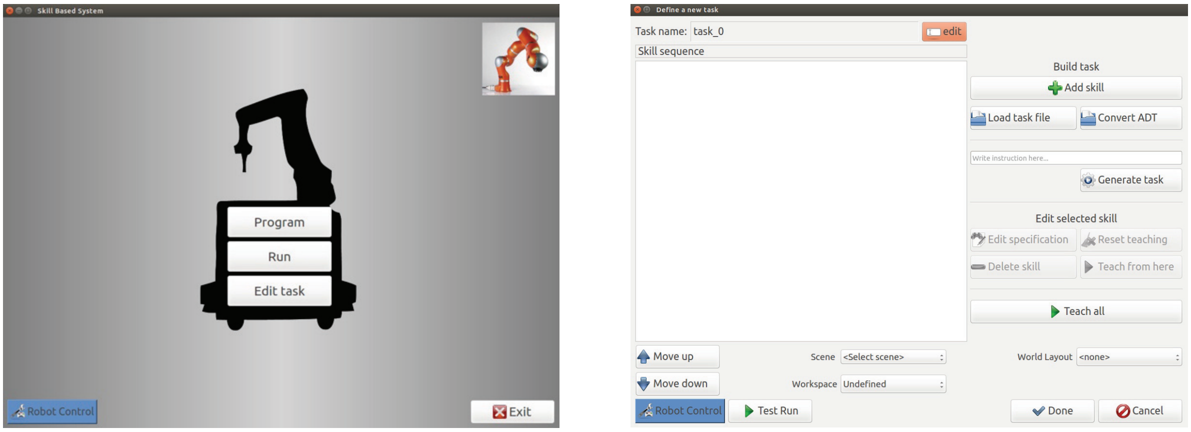

Fig. 4. (Left) The main menu in the SBS GUI; (Right) The menu for construction and editing of tasks.

3. Development and Experimental Results

2.3. An Intuitive Execution

In order to allow humans to interact with the system through the SBS a Human Machine Interface (HMI) in form of a GUI has been implemented. Schou et al. evaluate the intuitiveness of the GUI in respect to the teaching of skills. However, the intuitiveness of the execution, which is also conducted by the shop floor workers, is not covered. [15] Since the shop floor workers are both supposed to teach and execute skills with the robot in a cobot manner a GUI is required, which is user-friendly both for the teaching and execution phase.

By an investigation of the original GUI's execution menu, points of concern for improvement of the intuitiveness were identified. Those points of concern are, the number of options and variables an operator has to choose from, a missing intuitive path to follow through the GUI, and missing explanatory text for the operator. However, a new execution GUI should maintain the flexible and dynamic connection between the programmed and taught missions and the execution, such that new missions will be added dynamically to the execution GUI.

In the original GUI's execution dialog, the user assembles a mission from tasks, which is then executed. The user thus has to know the sequence of tasks required for the mission. As a mission can contain any combination of tasks, infinite different missions are possible, as shown in Fig. 5 (Left). The new GUI eliminates the problem of assembling missions and enables the operator to choose from a finite number of predefined missions.

In order to choose a certain mission, the user has to navigate through given options. The new GUI is breaking the missions down into specific parameters, which combined in a certain way leads to one unique mission. The user can navigate through the GUI by selecting from broad to narrow parameters until a specific mission is available for execution. Fig. 6 sketches a possible sequence of selected parameters leading to execution of a mission. The user chooses to use the “EASY RUN” execution menu. Then the user can choose which mission to carry out and the object the mission has to be performed on. Following this method, the user specifies the mission parameters until the execution layer is reached, in which the user can execute the corresponding mission.

During the selection of parameters, the user has access to information about previous selections and what other parameters has to be specified. Fig. 5 (Right) shows the information the user is given when selecting a parameter. In the top the overall headline “Mission” informs the user what has to be selected. A text under the headline instructs the user in detail what to do. When the user selects a parameter, which is presented as a push button in the GUI, they are brought to the next layer. In order to maintain the dynamic updating of the available missions in the “EASY RUN” GUI, every mission and its parameters are identified and dynamically plotted into the GUI. Thereby, new missions are directly available to be executed without coding them into the execution GUI.

A test was conducted to evaluate the intuitiveness of the new execution menu of the GUI. Five test subjects from three different educational backgrounds participated in the test. The test consisted of four individual missions. For each mission, the subject was asked to execute that specific mission. The first two missions were presented to the subject by giving them a description of the missions and the conditions in plain text, and additionally a sequence of the parameters they had to select in order to reach the given mission. The last two missions were only described by the plain text. The subjects attempted to execute each mission independently by following the descriptions. Before each task, the subject was given time to read the instructions and ask questions if necessary. For each mission the time from the beginning until the subject reached the execution was measured. The measured times can be seen in Tab. 1. Furthermore, the subjects were asked to rate the GUI on a scale from 1 to 5, where 1 is complex and 5 is easy, in terms of how easy and intuitive they thought the GUI was to use. Tab. 1 shows that the subjects rated the GUI three out of five times with the highest mark, while the remaining two rated it with the second highest. Hereby a safe conclusion would be that the GUI is indeed intuitive and easy to use. Furthermore, one can conclude that not only experts and students in the field of robotics find it intuitive, but also a workshop worker with no education related to robots.

Fig. 5. (Left) The original execute dialog for executing tasks or constructing and executing missions; (Right) Select mission parameters in the new execute dialog to find the mission to be executed.

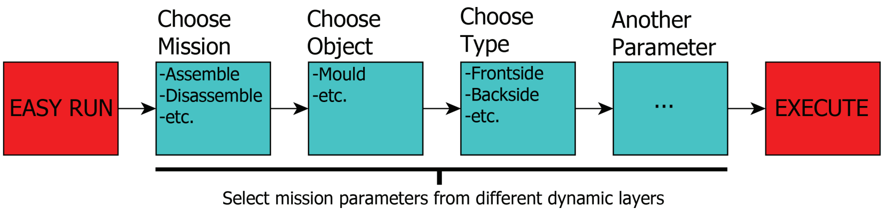

Fig. 6. Path to the execution of a mission based on selected mission parameters.

Test Subject	Education	Rating	Test 1 (t)	Test 2 (t)	Test 3 (t)	Test 4 (t)
1	Robot Expert	4	24 sec	16 sec	7 sec	7 sec
2	Robot Expert	5	13 sec	9 sec	10 sec	11 sec
3	Engineering Student	4	14 sec	11 sec	11 sec	12 sec
4	Engineering Student	5	8 sec	6 sec	7 sec	8 sec
5	Workshop Worker	5	21 sec	18 sec	24 sec	33 sec

Tab. 1. Results of the HRI test

2.4. The Screwing Skill

During the maintenance of injection moulds screwing is a crucial process. Today this operation is carried out by human workers and, therefore, cobots could become a valuable tool for the automation of such tasks. However, even robots known to be safe around humans do not fulfil the safety standards regarding cobots when a screwdriver tool is mounted. Solutions developed for screwing tasks need to consider such safety standards and still meet efficiency requirements. A screwing skill was developed for SBS disregarding the safety aspect in order to investigate the potential of skill-based collaborative screwing and hereafter to determine whether safety aspects for the application should be investigated.
In order to perform the initial test and to identify areas of improvement, a first iteration of the screwing skill was developed, which uses the last joint of the robot arm of the Little Helper 3 to rotate a manufactured aluminium 8mm hex key (Fig. 7. (Left)). The human screwing process is simulated by positioning and rotating the screwdriver tool inside a given screw. For the teaching of the screwing skill the operator has to teach the position of a given set of screws by locating the screwdriver tool into the screw head (Fig. 7 (Right)). When executed, the screwing skill is able to unscrew each of the taught screws one after another until a predefined height. For simplification of the task, a screw was defined as unscrewed when the predefined height was reached. The screwing skill enables the Little Helper robot to work as a cobot as it shares the workspace and keeps the human operator in the loop. While it supports the operations of the human it also relies on input from the human to do so.

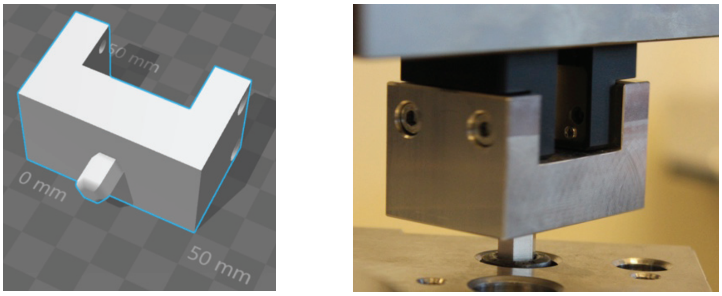

Fig. 7. (Left) A CAD-Model of the designed tool; (Right) The end result of the manufactured tool.

The cobot was able to unscrew a screw of 20 mm in length, in approximately 60 seconds, while a human could perform the same task in approximately 10 seconds. In terms of efficiency, the screwing skill cannot be executed faster than a human can do it, as long as the robot utilises a manual screwdriver instead of an electrical one. Nevertheless, the cobot is able to perform screwing in a collaborative manner, and can potentially carry out operations, while the operator works elsewhere. Furthermore, an electrical screwdriver tool instead of a key, which needs to be rotated to screw, could decrease the time used for the execution of the screw skill rapidly.

3. Conclusion

This paper describes the necessary steps in order to transform a mobile manipulator into a collaborative robot. The use of the cobot was made easier for inexperienced and untrained user by implementing an intuitive and adaptive GUI, and with the help of a screwing skill the cobot could assist workers in the maintenance of injection moulds. The Littler Helper 3 proved to be an appropriate robot, which could be programmed and implemented accordingly providing an easily controllable and adaptive robotic manipulator. Going forward, we aim to further enhance the safety specifications of the cobot by introducing adaptive vision algorithms that will control the execution according to the presence and the intentions of the human operator. Furthermore our target is to expand the scope of the application of the developed interfaces beyond just screwing skills but also cover several industrial maintenance tasks.

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