



Aalborg Universitet

AALBORG UNIVERSITY
DENMARK

A Dual-arm Collaborative Robot System for the Smart Factories of the Future

Filtborg Buhl, Jens; Grønhøj, Rune; Kjær Jørgensen, Jan; Mateus, Guilherme; Pinto, Daniela; Krunderup Sørensen, Jacob; Bøgh, Simon; Chrysostomou, Dimitrios

Published in:

29th International Conference on Flexible Automation and Intelligent Manufacturing

DOI (link to publication from Publisher):

[10.1016/j.promfg.2020.01.043](https://doi.org/10.1016/j.promfg.2020.01.043)

Creative Commons License
CC BY-NC-ND 4.0

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Filtborg Buhl, J., Grønhøj, R., Kjær Jørgensen, J., Mateus, G., Pinto, D., Krunderup Sørensen, J., Bøgh, S., & Chrysostomou, D. (2019). A Dual-arm Collaborative Robot System for the Smart Factories of the Future. In *29th International Conference on Flexible Automation and Intelligent Manufacturing: FAIM 2019* (Vol. 38, pp. 333-340). Elsevier. <https://doi.org/10.1016/j.promfg.2020.01.043>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.



29th International Conference on Flexible Automation and Intelligent Manufacturing
(FAIM2019), June 24-28, 2019, Limerick, Ireland.

A Dual-arm Collaborative Robot System for the Smart Factories of the Future

Jens F. Buhl^a, Rune Grønhøj^a, Jan K. Jørgensen^a, Guilherme Mateus^a, Daniela Pinto^a,
Jacob K. Sørensen^a, Simon Bøgh^b, Dimitrios Chrysostomou^{b*}

^aDept. of Materials and Production, Aalborg University, Fibigerstraede 16, Aalborg East, DK-9220, Denmark

^bRobotics & Automation Group, Dept. of Materials and Production, Aalborg University, Fibigerstraede 16, Aalborg East, DK-9220, Denmark

Abstract

In the era of Industry 4.0, collaborative robots have been one of the main pillars enabling flexible automation. This paper investigates the benefits of integrating a dual-arm collaborative robot system in a smart factory and an Industry 4.0 context with particular focus on solving complex industrial disassembly tasks. The increased human-like capabilities of the system stemming from two arms, dual tooling and advanced vision bring enhanced dexterity allowing for simultaneous control and synchronous movement of both robot arms and product components. The presented work addresses the design considerations and overall hardware and software architecture of Little Helper 7, a collaborative robot system which consists of commercial off-the-shelf components, and ROS as a middleware for data communication, motion planning, 3D vision, and control. Preliminary experiments performed with Little Helper 7, demonstrate promising system capabilities such as path planning for both arms for synchronous movement while avoiding collision and accurate estimation of the location of objects in the workspace.

© 2019 The Authors. Published by Elsevier B.V.

This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

Peer-review under responsibility of the scientific committee of the Flexible Automation and Intelligent Manufacturing 2019 (FAIM 2019)

Keywords: Collaborative robots, Dual-arm robot, Smart manufacturing, Disassembly robot, Industry 4.0

* Corresponding author. Tel.: +45 2118 1918.

E-mail address: dimi@mp.aau.dk

1. Introduction

Digital transformation provides us with a myriad of new capabilities and functionalities [1]; however, the increasing number of electronic devices and the fierce competition of the tech companies for satisfying customer needs, creates technological redundancy and, therefore, alarming amounts of electronic waste [2]. At the same time, the robotics market, and especially collaborative robots, is proliferating with novel, user friendly, single and dual arm robot systems [3-6] that can assist with a plentiful of operations e.g. maintenance tasks [7], part feeding [8], assembly [9] and most importantly disassembly [10]. More specifically, the disassembly of electronic components is a growing area of interest in the research community [11], due to the throwaway consumerism culture which currently results in a tremendous waste of valuable materials. Torres used a combination of a 5 DoF Scorbot ER-IX with a y-z cartesian mobile vision system, for the disassembly of personal computers [12], while DiFilippo used an ENCore 2s robotic platform to remove screws from laptops identified by a vision system [13] and Kopacek explored ways to remove components from PCBs for recovery of critical metals [14].

In this paper, we describe a dual-arm collaborative robot system (Fig 1a) that enables flexible manufacturing tasks and is focused on the disassembly of mock up mobile phones. The robot is installed at the end of the line of an Industry 4.0, modular production line comprised by FESTO Cyber-Physical (CP) modules [15]. The FESTO CP Factory (Fig 1b) is built up by several modules, each consisting of an individual cyber physical system, which is then connected through a network. The main product of the depicted FESTO CP Factory is mock up mobile phones in several variations. We assume the robot is given the sequence of the assembly flow of the mock-up products and which components are potentially missing due to errors in the production. The goal of the robot is to disassemble the phone successfully and identify any defects or missing components.

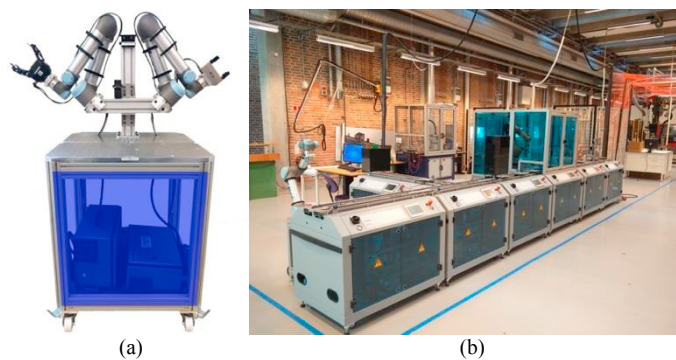


Fig. 1 (a) Little Helper 7 and (b) FESTO CP Factory.

1.1 Background

Little Helper (LH) is a family of robotic platforms which has been under development by researchers and students in the Robotics and Automation Group of Aalborg University. The various LHs versions had various areas of focus and improvements over the last decade (Fig. 2). Ultimately the overall view of the previous versions can be

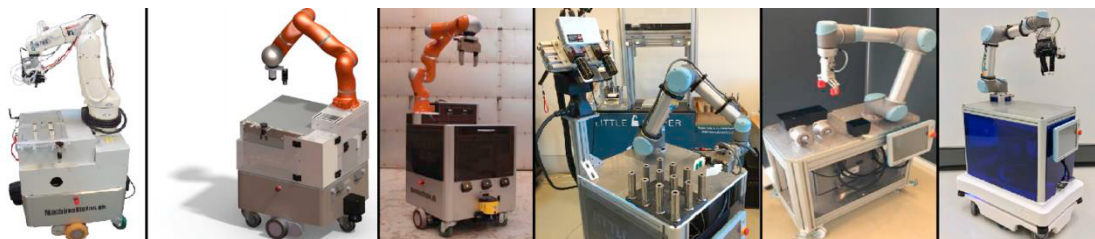


Fig. 2. Evolution of the Little Helper platform, in chronological order starting from the left: Little Helper 1 (2008) - Little helper 6 (2017)

taken into consideration for the creation of the seventh iteration of the platform, LH7.

The first three versions shared the Neobotix MP-700 as their mobile platform, LH6 had MiR100, and the remaining ones had a moveable non-autonomous platform. Regarding the manipulators, the first LH project had Adept Viper s650, LH2 and LH3 had KUKA LWR, and all following versions use the UR5 robot arm. Although multiple Little Helpers share hardware elements, an evolution throughout the years can be observed, though, always using a single manipulator. However, according to the tests performed in [8], LH6 suffered from limitations when trying to perform part feeding tasks, due to the usage of a single manipulator. Therefore, at the time the sixth iteration was built and tested; it was assumed that the implementation of dual-arm robotic manipulation is necessary for the natural progression of the system.

2. Development Approach and System Setup

2.1 Lean Start-up

The development of LH7 was based on the principles of the Lean Start-Up method where several iterations of development occur where the focus is concentrated on generating iterations of minimum viable products and work towards the development of the final prototype based on received feedback of each significant iteration. Therefore, two major iterations are documented in this paper containing many more minor ones which led to the final design of the robot system. The first iteration covered several minor iterations regarding the design and architecture of the system which was validated with a case of opening a glass bottle. The second iteration covered the disassembly of the mock up products in connection with the FESTO CP Factory.

2.2 Hardware overview

Little Helper 7 utilizes two Universal Robots - UR5 industrial manipulators, an Intel RealSense D435, a Schunk WSG 50-110 parallel gripper, and a Robotiq 3-finger gripper. Due to the integration of the collaborative UR5s and the vision system, the platform has the prospect of sharing the workspace with humans and collaborate safely. An exploded view of the system described above can be seen in Fig 3. These hardware components communicate with each other over a gigabit-LAN network and controlled by an off-the-shelf workstation running ROS Kinetic.

2.3 Software architecture

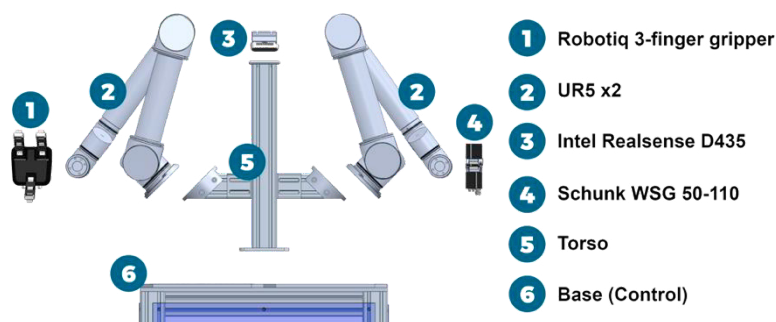


Fig. 3. Graphic illustration of the hardware elements of Little Helper 7.

The system also uses the motion planning framework MoveIt! on top of ROS, in order to calculate kinematics, perform motion planning, and collision checking between the two robotic arms. The vision system is integrated by the usage of the OpenCV library. The overall software architecture and the data flow diagram are depicted in Fig. 4.

3. Methodology

3.1 Opening bottles

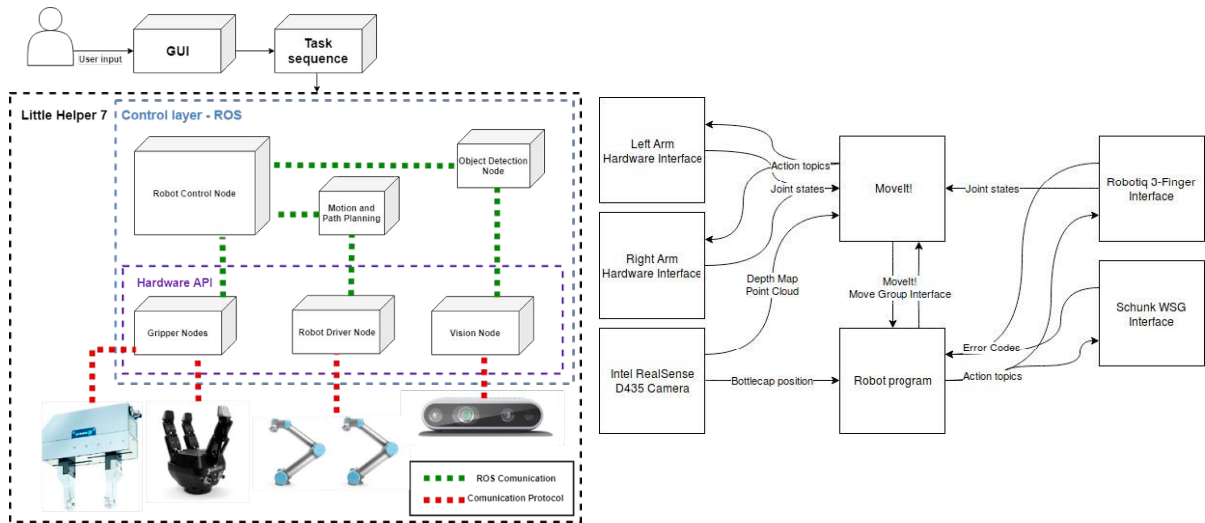


Fig. 4. *Left*: Overall software architecture of LH7; *Right*: the data flow diagram of LH7.

The first use case applied to benchmark the system during its integration phase was focused on the task of detecting the position, grasping and opening a glass bottle. Fig. 6 presents the different stages of the process. The process begins by locating the position of the bottle with the vision system in a 2D cartesian plane, publishing the effective location of the bottle cap to a ROS topic accessible by the robots, which then use this information to begin their task (A). Following this initial step, the left manipulator, using the Schunk gripper, grasps the bottle from above, lifting it in the workspace (B). The second manipulator is then actuated into grasping the bottle by its sides with the WSG gripper (C) and performs the motion to a position where the bottle cap is placed in a fixed opener, proceeding to perform an arc movement, where the cap is removed (D). Finally, the opened bottle is grasped, yet again, by the left manipulator and placed down on the table in front of the system.

In order for this sequence to be successful, dynamic motion planning of the two robot arms is of great importance. Fig 5 showcases LH7 in several positions in the RVIZ environment during the execution of the task in-hand. Calibration of the platform is also crucial. Fig. 7 illustrates the coordinate frames associated with the whole system (Fig 7a), the hand-eye (Fig 7b) and camera calibration (Fig 7c) procedure. In order to successfully detect the cap of the bottle, a straightforward algorithm for template matching and homography calculation was utilized. Firstly, SIFT features were detected across the whole image and then isolated in the bottle's label. These features were then described using SURF due to better performance and then by using FLANN Based matching and

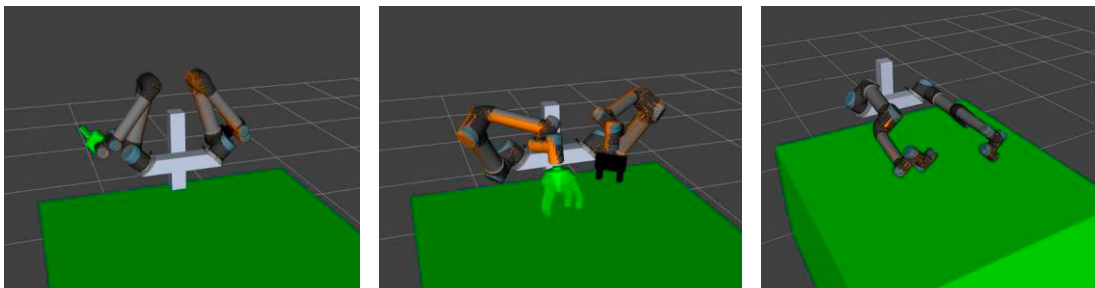


Fig. 5. Little Helper 7 in home position (*left*), ready position (*middle*) and planning phase (*right*).

randomized kd-trees all strong features were matched with the trained label of the bottle. After applying RANSAC to remove outliers and select the best features for the homography calculation, the detection of the bottle cap was possible and successful.

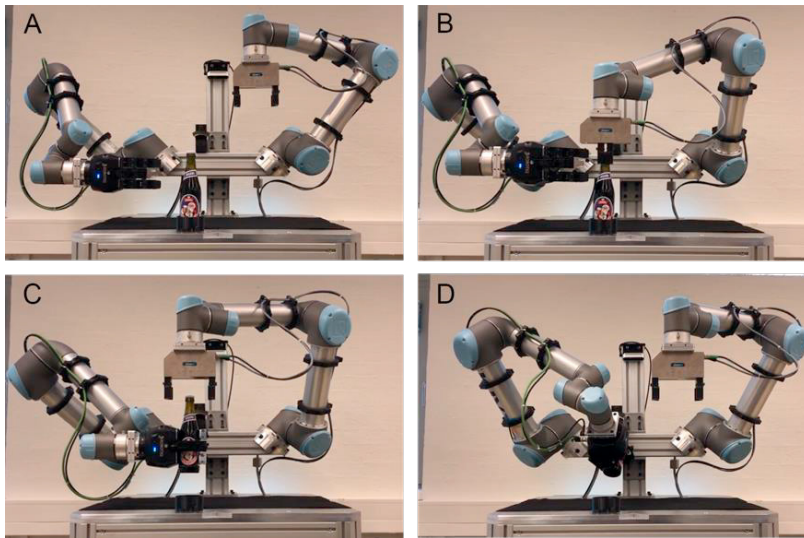


Fig. 6. Sequence for opening bottles with LH7.

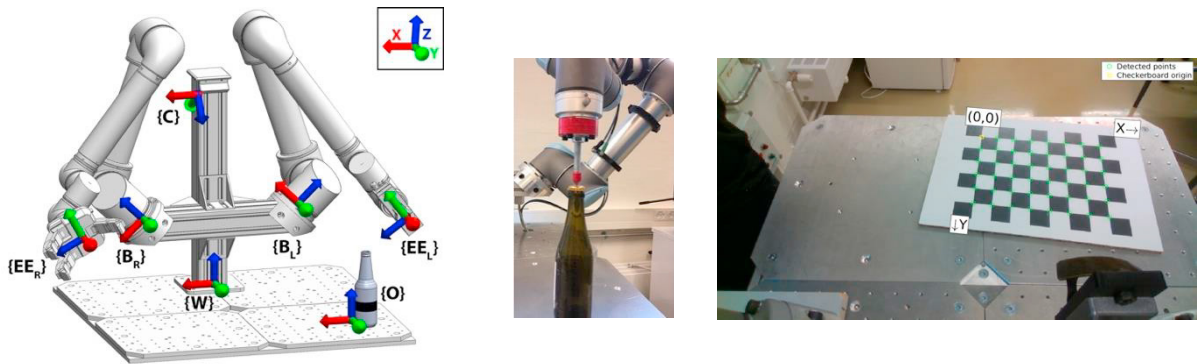


Fig. 7. Left: Coordinate frames associated with LH7; Middle: Hand-eye calibration; Right: Camera calibration.

3.2 Disassembly of mock up mobile phones

After the successful iteration with the task of the bottle opening, the system was now ready to be introduced to the FESTO CP Factory application and the disassembly of the mock-up product. The parts of the product are shown in Fig. 8 while the assembly flow in order to assemble the parts is illustrated in Fig. 9. A 12-step process is necessary in order to reverse the assembly flow of the mock-up product and successfully disassemble the product. In the sequence, depicted in Fig. 10, LH7 waits for the pallet to arrive at the checkpoint carrying the assembled part. After receiving a confirmation signal from the PLC of the FESTO CP module, LH7 initiates the grasping of the product from the pallet. Having grasped the product with the right arm, in steps 2-4, the left robot arm removes the top cover of the product and delivers it in a box. The following steps 5-11 involve the removal of the two fuses using the left robot arm and the special designed fingers. The PCB is first held by the gripper (in steps 6 and 7) in order to allow the bottom cover to fall into a collection box. Later, the two fuses are taken away from the PCB and

delivered in a dedicated collection box for recycled use in the assembly flow of the product in the following orders. Step 12 concludes the disassembly sequence by delivering the PCB to a third collection box.



Fig. 8. The parts of the mock up product.

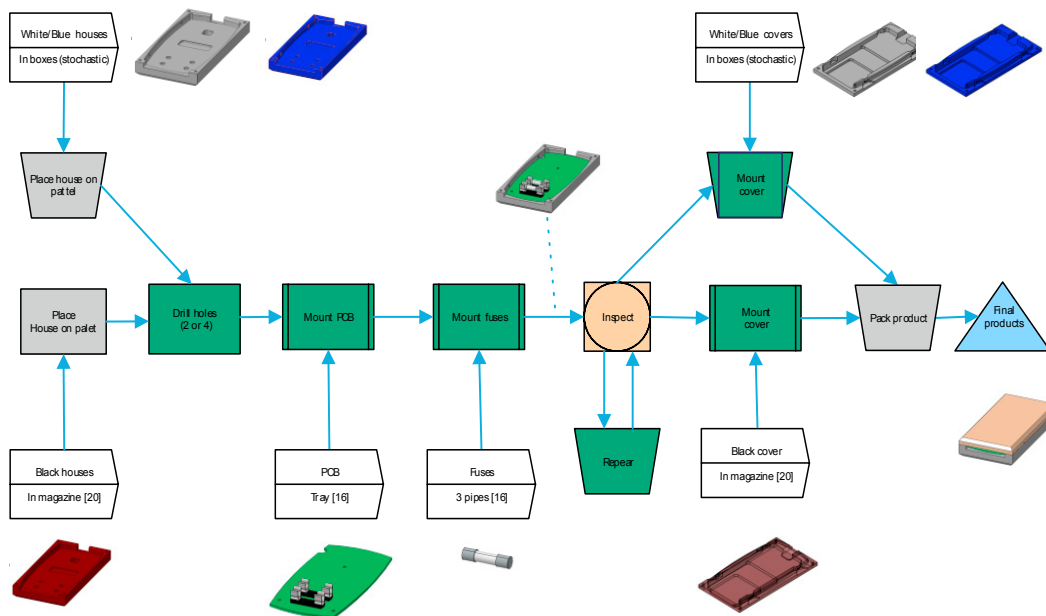


Fig. 9. Assembly flow of the mock up product.

3.3 Evaluation

In order to evaluate the performance of the LH7 during the execution of the two tasks, we measured the times where the LH7 successfully detected, grasped and opened the bottle in the first case, while in the disassembly our focus was the final cycle time. LH7 managed to detect the bottle 90% of the time. The unsuccessful detections were caused due to the glass surface of the bottle. The challenging surface caused several faulty matches and failures of the SURF descriptor, however, after a successful detection of the bottle, LH7 managed to grasp the bottle and open it successfully every time.

A human operator can complete the disassembly task in 9 seconds. It is natural to assume that a collaborative robot system working in limited speeds dictated by safety standards it is not possible to reach such performance. Instead, LH7 can complete the disassembly task in 72 seconds instead without any failures in detection, grasping or manipulation of the parts.

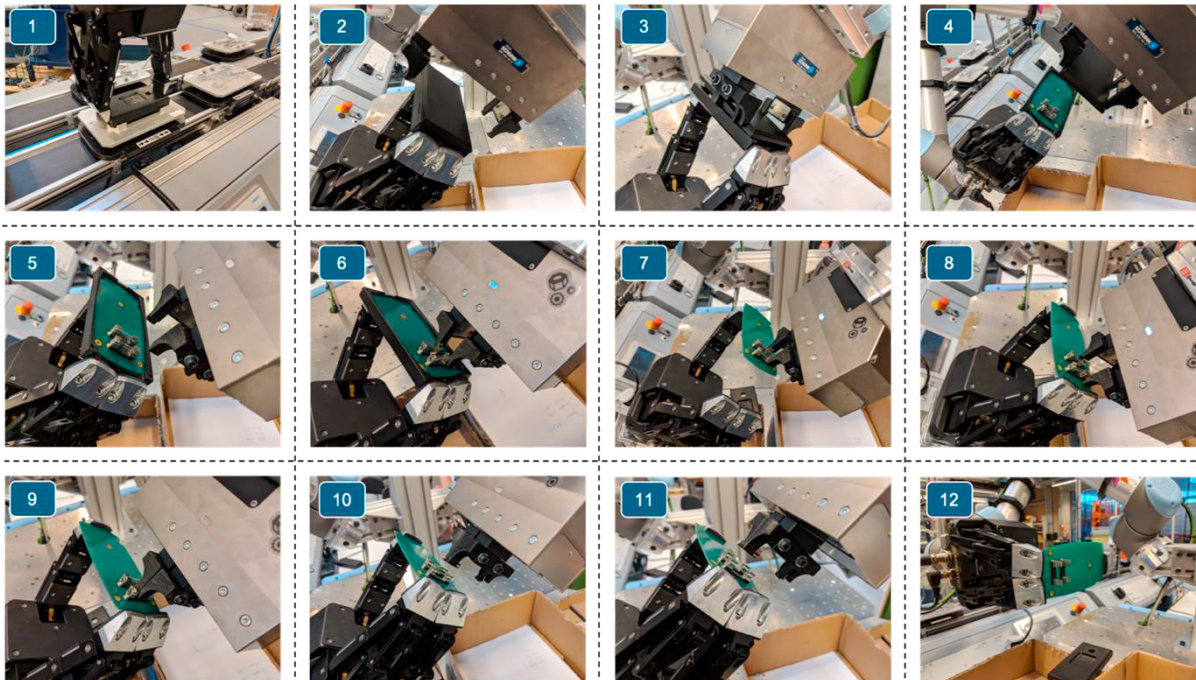


Fig. 10. The 12-step process of the disassembly of the mock-up mobile phone.

4. Discussion

Our goal was to create a collaborative dual-arm robot system, flexible enough to enable the execution of several tasks located in the service and manufacturing domains. Little Helper 7 represents our early progress towards this goal, demonstrating that a modular hardware system combined with motion planning, vision and manipulation skills based on ROS is sufficient to accomplish the challenging task of disassembly of electronics and opening glass bottles. Its performance is not yet comparable to human operators; however, its main task is to create possibilities of sharing the workspace freely with human operators instead of replacing them. In principle, LH7 is a collaborative robot and its final design derived after many iterations where the presence of any human operators inside its workspace is seriously considered as a defining factor. At this stage of development, LH7 incorporates passive safety measures originating from the safety limits and construction of the robot arms and the platform. Thus, there are no sharp edges in the movable platform or in the torso that could potentially harm the operators. Unfortunately, the chosen grippers are not designed with close collaboration in mind since they have plenty of sharp corners, but they are subject to change in the future versions of Little Helper 7.

5. Future directions

Little Helper 7 enables us to explore more application areas of collaborative robotics. It is still in its infancy, and there are plenty of areas for improvements. An area where LH7 is lacking is collaboration and safety when working close to humans. A crucial factor in such collaboration is the prediction and adaptation to mutual intentions. We are working towards the integration of a visual system able to project the intentions of LH7 to the operator, and at the same time, we plan to incorporate a laser scanner on the platform to significantly improve safety and the human-robot collaboration. In future versions, we also plan to use compliant and force control to compensate for uncertainties in the production environment. At the same time, many of the operations could be upgraded to include machine learning techniques in areas such as the manipulation and perception of the parts. Learning can also be

incorporated in force and torque trajectories to facilitate the disassembly according to the taught trajectories from an operator. The detection rate of the parts could be significantly improved with the integration of a second camera on one of the wrists of the robot to provide close up views of the object and facilitate with grasp planning. Additionally, other than software, a tool changer could enable LH7 to accomplish a plethora of tasks involving a variety of different tips and grippers that could easily be exchanged during disassembly operations. Finally, a pan-tilt unit integrated into the torso of LH7 could carry another camera to provide with enhanced awareness of its workspace, more accurate detection of human operators and improved safety capabilities.

6. Conclusion

This paper presents the seventh iteration of the Little Helper platform and focuses on the presentation of its system architecture and its main capabilities. A FESTO CP Factory was used to provide the challenges of a real production environment and serve as a testbed for the task of the disassembly of mock up mobile phones. The key feature of Little Helper 7 is the incorporation of two robotic manipulators, for the first time in the history of the Little Helper robotic systems, in addition to a plethora of auxiliary equipment to offer a higher degree of flexibility and dexterity in modern production. The robotic platform is modular and flexible enough to handle two different tasks, two grippers and multiple pairs of fingertips in order to accomplish two diverse tasks. In order to check the feasibility of the initial design and integration of the system a service task of opening a bottle was executed successfully. The valuable lessons learned from the execution of this task led us to the final design of the LH7 used for a production task focused on the disassembly of mock-up mobile phones. LH7 proved to be robust and flexible enough to handle diverse tasks both in the service and manufacturing domain with remarkable accuracy and performance.

References

- [1] Matt, Christian, Thomas Hess, and Alexander Benlian. "Digital transformation strategies." *Business & Information Systems Engineering* 57, no. 5 (2015): 339-343.
- [2] Robinson, Brett H. "E-waste: an assessment of global production and environmental impacts." *Science of the total environment* 408, no. 2 (2009): 183-191.
- [3] Smith, Christian, Yiannis Karayiannidis, Lazaros Nalpantidis, Xavi Gratal, Peng Qi, Dimos V. Dimarogonas, and Danica Kragic. "Dual arm manipulation—A survey." *Robotics and Autonomous systems* 60, no. 10 (2012): 1340-1353.
- [4] Stolt, Andreas, Magnus Linderroth, Anders Robertsson, and Rolf Johansson. "Force controlled robotic assembly without a force sensor." In *2012 IEEE International Conference on Robotics and Automation*, pp. 1538-1543. IEEE, 2012.
- [5] Fitzgerald, Cliff. "Developing baxter." In *2013 IEEE Conference on Technologies for Practical Robot Applications (TePRA)*, pp. 1-6. IEEE, 2013.
- [6] Garage, Willow. "Overview of the PR2 robot." (2009).
- [7] Koch, Paul J., Marike K. van Amstel, Patrycja Dębska, Moritz A. Thormann, Adrian J. Tetzlaff, Simon Bøgh, and Dimitrios Chrysostomou. "A skill-based robot co-worker for industrial maintenance tasks." *Procedia Manufacturing* 11 (2017): 83-90.
- [8] Andersen, Rasmus Eckholdt, Emil Blixt Hansen, David Cerny, Steffen Madsen, Biranavan Pulendralingam, Simon Bøgh, and Dimitrios Chrysostomou. "Integration of a skill-based collaborative mobile robot in a smart cyber-physical environment." *Procedia Manufacturing* 11 (2017): 114-123.
- [9] Madsen, Ole, Simon Bøgh, Casper Schou, Rasmus Skovgaard Andersen, Jens Skov Damgaard, Mikkel Rath Pedersen, and Volker Krüger. "Integration of mobile manipulators in an industrial production." *Industrial Robot: An International Journal* 42, no. 1 (2015): 11-18.
- [10] Wegener, Kathrin, Wei Hua Chen, Franz Dietrich, Klaus Dröder, and Sami Kara. "Robot assisted disassembly for the recycling of electric vehicle batteries." *Procedia Cirp* 29 (2015): 716-721.
- [11] Alvarez-de-los-Mozos, Esther, and Arantxa Renteria. "Collaborative robots in e-waste management." *Procedia Manufacturing* 11 (2017): 55-62.
- [12] Torres, Fernando, Pablo Gil, S. T. Puente, Jorge Pomares, and R. Aracil. "Automatic PC disassembly for component recovery." *The international journal of advanced manufacturing technology* 23, no. 1-2 (2004): 39-46.
- [13] DiFilippo, Nicholas M., and Musa K. Jouaneh. "A System Combining Force and Vision Sensing for Automated Screw Removal on Laptops." *IEEE Transactions on Automation Science and Engineering* 15, no. 2 (2018): 887-895.
- [14] Kopacek, Bernd. "Intelligent Disassembly of components from printed circuit boards to enable re-use and more efficient recovery of critical metals." In *2016 Electronics Goes Green 2016+(EGG)*, pp. 1-8. IEEE, 2016.
- [15] FESTO CP Factory modules <https://www.festo-didactic.com/int-en/highlights/qualification-for-industry-4.0/cyber-physical-factory/> [Accessed 24 Feb. 2019]