An experimental human-robot collaborative disassembly cell

Huang, Jun; Pham, Duc Truong; Li, Ruiya; Qu, Mo; Wang, Yongjing; Kerin, Mairi; Su, Shizhong; Ji, Chunqian; Mahomed, Omar; Khalil, Riham; Stockton, David; Xu, Wenjun; Liu, Quan; Zhou, Zude

DOI:
10.1016/j.cie.2021.107189

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***Abstract*: Disassembly is the first operation in the remanufacture, repair and recycling of products that have reached the end of their service life. Both productivity and flexibility should be considered when using robots to carry out disassembly due to the complexities associated with the products returned for remanufacturing. Human-robot collaboration is a flexible semi-automated approach to mitigate against the effects of uncertainties in the frequency, quantity and quality of those End-of-Life (EoL) products.**

This paper presents a new experimental robotic disassembly cell comprising two collaborative robots and a human operator. The robots and the operator can work safely in tandem for individual, parallel or common disassembly tasks in a shared workspace. Active compliance control is employed by the collaborative robots to achieve complex disassembly tasks and safe human-robot interaction. The human operator communicates with the robots using a new method based on touch sensing combined with position control. The paper first provides a short literature review of robotic disassembly and human-robot collaboration focusing on disassembly. It then describes the collaborative disassembly demonstration cell. Finally, the paper details a case study highlighting the capabilities of the cell. The case study shows that the automation of complex disassembly tasks is feasible and has the potential to release people from tedious and repetitive work.

***Keywords*: Human-robot collaboration; disassembly; robotic disassembly; robotic cell; remanufacturing.**

1. Introduction

Remanufacturing is important from a socio-economic perspective, contributing to both environmental protection and resource conservation through reducing waste to landfill, saving energy and raw materials, and causing lower greenhouse gas emissions (Pham, 2019; Ramírez et al., 2020). Disassembly is a critical step in remanufacturing of returned End-of-Life (EoL) products, enabling a circular economy (Duflou et al., 2008; Vongbunyong et al., 2013a). However, at present, most disassembly operations are carried out manually, which is very labour intensive, has low efficiency and is generally unstimulating for the operations team (Merdan et al., 2010). In many ways, disassembly is more difficult than assembly to automate due to the uncertain shapes, sizes and physical conditions of used products. Any autonomous disassembly approach requires high flexibility to handle these uncertainties to make it technically and economically feasible for more companies to adopt.

In recent years, human-robot collaboration (HRC) has become a new frontier in industrial manufacturing by combining the advantages of industrial robots with high levels of accuracy, speed and repeatability, with human operators who have superior flexibility, cognitive and dexterity skills (Matsas et al., 2017; Ogenyi et al., 2019; Villani et al., 2018). Human-robot collaborative disassembly was proposed to deal with EoL products for sustainable manufacturing (Liu et al., 2019). Meanwhile, collaborative robots (or "cobots") have emerged from many industrial robot manufacturers including the LBR iiwa range from KUKA (KUKA, 2018), the UR range from Universal Robots (UNIVERSAL ROBOTS, 2018), the YuMi from ABB (ABB, 2018), the CR range from Fanuc (FANUC, 2018), and the TX2 range from Staubli (STAUBLI, 2018). All are commercially available, facilitating the wider application of industrial human-robot collaboration in manufacturing (Bo et al., 2016; Fernandez et al., 2017; W. Wang et al., 2019). Using these cobots enables direct interactions with human operators in a shared workspace without safety guarding impeding collaboration. Effective HRC involves robots working alongside humans safely (as co-workers) to perform tasks jointly or independently.

We previously described a method for disassembling press-fitted components using HRC and demonstrated it on the disassembly of an automotive water pump by a collaborative robot (Huang et al., 2019). In this paper, a new HRC disassembly cell is presented that involves two collaborative robots working alongside a human operator within a shared workspace. In HRC, robots increase cell productivity, and human operators provide higher flexibility and adaptability to handle disassembly uncertainties. Human operators can be released from repetitive and potentially dangerous disassembly operations, allowing them to focus on processes requiring flexibility and adaptability, or high-value adding work such as cognitive information processing and decision making for unpredictable events.

The engineering techniques employed in the robotic cell include active compliance control of robots based on force and torque sensing, automated screw unfastening using autonomous screw-head searching algorithms, and human-robot interaction with a combination of touch sensing and position control. The engineering contributions of this work can be summarised as follows.

1) Proposing the general architecture of an experimental HRC disassembly cell and the main steps for its development. The cell constructed in this research features both human-robot and robot-robot collaboration.
2) Demonstrating the use of collaborative robots with active compliance control to achieve complex disassembly tasks and safe human-robot interaction.
3) Integrating impact (touch) and position control to give the operator a safe and convenient method of issuing start/stop commands to a robot.
4) Showing that the automation of a complex disassembly task, such as the dismantling of an automotive turbocharger, is feasible through combining the flexibility of the human operator and the ability of the robots to perform repetitive operations with ease.

This paper is organised as follows. Section 2 gives a short literature review covering robotic disassembly and human-robot collaboration. The new robotic disassembly cell is described in Section 3. To demonstrate the capabilities of the cell, a case study is carried out using HRC disassembly of an automotive turbocharger. This is reported in Section 4. Finally, Section 5 concludes the paper and provides suggestions for future work.

2. Related Work

As a means to contribute to sustainable manufacturing and a circular economy, the task of disassembly has received much academic and industrial attention (Duflou et al., 2008; Lambert & Gupta, 2016). Robotic disassembly is a key enabling technology of autonomous remanufacturing to increase productivity and improve ergonomics (AUTOREMAN project, 2020). Disassembly is not merely the reverse of assembly. It can be more challenging than assembly to robotise due to the uncertainties of the returned products and disassembly processes (Priyono et al., 2016; Vongbunyong et al., 2017). However, studies in robotic assembly such as those by (Foumani et al., 2017a, 2017b and 2020) may still provide useful guidelines for developing robotic systems for disassembly tasks. Human-robot collaborative disassembly offers a semi-autonomous approach suitable for disassembly tasks that are too complex to be carried out by robots alone or too expensive to be automated with special robotic tools and systems (Maurtua et al., 2017).

2.1. Robotic Disassembly

Today, the process of disassembly is generally carried out by human operators using hand tools. It is labour intensive, with low efficiency and poor ergonomics, with products like batteries known to be harmful to operators' health (J. Li et al., 2018). With an increase in environmental awareness and rising labour costs, significant attempts to automate disassembly processes using industrial robots have been made (Vongbunyong & Chen, 2015; Vongbunyong et al., 2013b).

Vision-based cognitive robots were employed to address the problems of variations in disassembly processes (Vongbunyong et al., 2013b). A cognitive robotic agent was designed to handle variations in product structure, operation plan, and process parameters. Human assistance was suggested to resolve issues during disassembly. A multi-sensorial system including visual, force and tactile sensors was adopted in a robotic disassembly cell (Gil et al., 2007). The system was validated on the disassembly of personal computer (PC) components. The authors suggested future work including the distribution of disassembly tasks to human operators in a shared working area. A robot assistant was used in a hybrid disassembly workstation to perform the task of unscrewing (Chen et al., 2014). A robot-driven disassembly sequence generator was proposed for automated disassembly of EoL electronic products (ElSayed et al., 2012). A robotic cell was developed with an industrial robot and a camera, and a Genetic Algorithm was employed to optimise disassembly sequences. A sequence planning method using an enhanced discrete Bees Algorithm was presented for robotic disassembly to increase disassembly efficiency (Liu et al., 2017). The results showed that the proposed method could generate more efficient robotic disassembly sequences than traditional methods.

An automatic disassembly robotic cell was proposed for disassembly of computers, and a task planner was designed for the distribution of disassembly tasks among robots using decision trees (Torres et al., 2009). Human operators were not involved in the cell. Based on industrial robots, a functional architecture of an automatic disassembly system was designed for EoL vehicles (Sánchez et al., 2008). An automated approach was developed for robotic disassembly of EoL electric vehicles (Li et al., 2014). A systematic framework was described for the approach development. To deal with electronic waste, a robot disassembly cell was introduced for obsolete TV sets and monitors (Scholz et al., 1999). Two industrial robots were employed for disassembly and handling in the cell. A joint decision-making model was established for system scheme selection and recovery route assignment of automated disassembly, and validated on a case study involving the disassembly of waste electric meters (Tao et al., 2018). However, the proposed robotic disassembly cell was not built for the real demonstration of automated disassembly. A new robot was developed for iPhone disassembly to recover valuable materials from EoL iPhones (Deahl, 2018). A collaborative robot was employed in a disassembly cell to work with a human operator to disassemble electric vehicle batteries (Wegener et al., 2015). The robot carried out the task of unscrewing. Vision-based detection was suggested to acquire information in the location of the bolts to increase disassembly efficiency in future work.

In all the work reviewed above, except (Wegener et al., 2015), the robots used were conventional industrial robots. In addition, human operators were not intensively involved in disassembly operations. More flexibility of the robotic disassembly cell was needed during disassembly processes. In the semi-autonomous cell presented in this paper, two cobots were employed to demonstrate both human-robot and robot-robot collaboration.

2.2. Human-Robot Collaboration (HRC) in Industrial Environments

As already stated, HRC enables human operators and robots to contribute their specific abilities and complement each other in an open, guarding-free shared environment, providing flexible and productive solutions in smart factories (Charalambous et al., 2017; Robla et al., 2017). In recent years, HRC has been adopted by a small number of companies, particularly in the automotive and electronic sectors, but not for disassembly operations thus far.

An overview of the state of the art of HRC in industrial settings was reported, which identified the main challenges of HRC as safety issues (such as safety standards and collaborative operating modes), user interfaces (such as programming approaches and interaction modes), and design methods (such as control laws, sensors, and task allocation and planning) (Villani et al., 2018). Four collaborative modes were identified in the ISO 10218-1/2 robot safety standards. They are safety-rated monitored stop (SMS), hand guiding (HG), speed and separation monitoring (SSM), and power and force limiting (PFL). A review of safety systems enabling safe human-robot collaboration in industrial robotic environments was also presented (Robla et al., 2017). A risk assessment was carried out for the layout design of a collaborative assembly cell for flywheel housing covers on engine blocks using a large industrial robot (Gopinath et al., 2017). A review of HRC research and its classification was introduced and an HRC assembly system for industrial tasks such as food packaging, aeronautical component assembly and automotive engine assembly was developed (Wang et al., 2017). Agent multiplicity was used for HRC classification, which was distinguished between single, multiple and team. A disassembly sequence planning method using orthogonal arrays was designed for EoL processes such as recycling and reuse (Alshibli et al., 2019).

Based on capability indicators, an approach was proposed to identify applications of collaborative robots in powertrain assembly (Schröter et al., 2016). The indicators included cycle time, additional invest, process quality, and work quality. Multimodal communication using speech and gestures was developed and implemented for HRC in assembly and deburring operations (Maurtua et al., 2017). The approach was explained by using real collaborations between a robot and a worker. A decision-making method within an HRC framework was presented for HR task allocation, planning and implementation in the assembly of an automotive hydraulic pump (Tsarouchi et al., 2017). Based on two KUKA iiwa lightweight robots, a dual-arm robotic system was developed for industrial HRC with multiple sensor modalities, and validated at a gearbox assembly station at a Volkswagen factory (Fernandez et al., 2017). The feasibility of HRC was investigated for a case study involving the assembly of brake discs with a decision-making method and task allocation method proposed (Heydaryan et al., 2018). To deal with unpredictable lot sizes and volumes as well as significant design variation of EV batteries, HRC was investigated and implemented for safe, flexible and productive disassembly of batteries (Kwade & Diekmann, 2018; Wegener et al., 2015).

Due to the advantages of HRC, an increasing number of applications in production processes using collaborative robots have been reported in automotive industry. The Spartanburg plant was the first BMW Group production facility to implement HRC for door assembly in series production in 2013 (BMW Group, 2013). HRC was initially used to release operators from non-ergonomic work in engine production processes at the Salzgitter plant in the Volkswagen Group in 2013 (Kite, 2013). HRC was first applied by Audi in final assembly at its main plant in Ingolstadt in 2015 (Leggett, 2015). Collaborative robots were employed to work on an assembly line at Ford's factory in Cologne (Zaleski, 2016) and a collaborative robot was used to work with an operator to apply sealant to vehicles at the Jaguar Land Rover Castle Bromwich plant (Roberts, 2018).

The above review shows that there have not been many applications of robots to disassembly operations. As mentioned previously, this is because disassembly is hard to robotise, given the high degrees of uncertainty involved and the difficulty with dismantling distorted, rusty or otherwise damaged EoL products. Semi-autonomous disassembly cells where humans

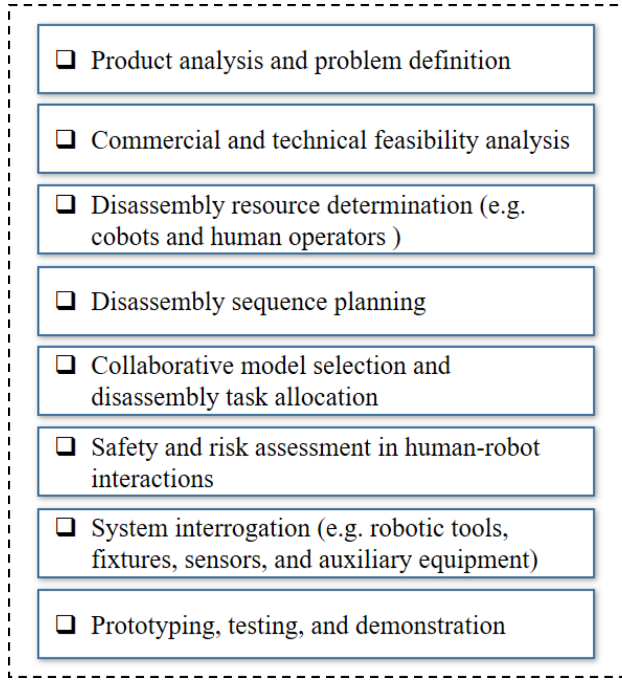

Fig. 1. General steps for the development and implementation of an HRC disassembly cell.

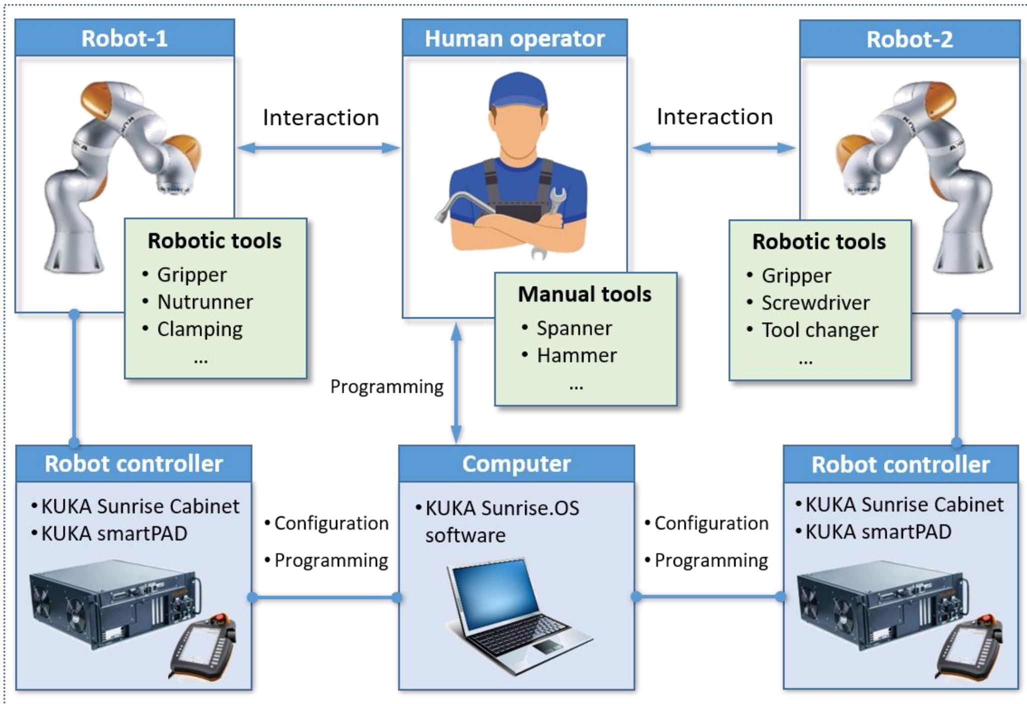

Fig. 2. Framework architecture of the proposed robotic system for collaborative disassembly.

and robots collaborate with one another should be able to handle uncertainty and disassembly problems related to the poor condition of EoL products without requiring excessive capital investment. In addition, HRC disassembly can decrease reconfiguration time for different kinds of products. Our previous research showed that disassembly is not the simple reverse of assembly and requires different techniques for operations such as removing bearings from shafts (Zhang et al., 2019) and unfastening screws (Li et al., 2020).

3. Description of the Proposed Robotic Disassembly Cell

Fig.1 summarises the general steps for the development and implementation of an HRC disassembly cell. First, disassembly requirements and problems are identified via product analysis. Then, commercial and technical feasibility analysis is carried out, considering the required disassembly resources such as collaborative robots and human operators. The disassembly process is divided into detailed disassembly tasks and operations. Suitable disassembly sequences and collaborative models are then selected. Next, disassembly tasks are assigned to robots and human operators. Safety and risk assessment are conducted. Ergonomic evaluation can be conducted to ensure human health and safety and increase efficiency (Battini et al., 2011 and 2015). Finally, the robotic system is assembled, prototyped and tested.

A new robotic disassembly cell has been designed and developed to demonstrate HRC for complex disassembly operations, as well as to act as a test bed for the development and validation of robotic disassembly strategies and technologies. This section describes the architecture of the robotic disassembly system including the communication links between the hardware components. The chosen methods of human-robot interaction and task allocation are also introduced.

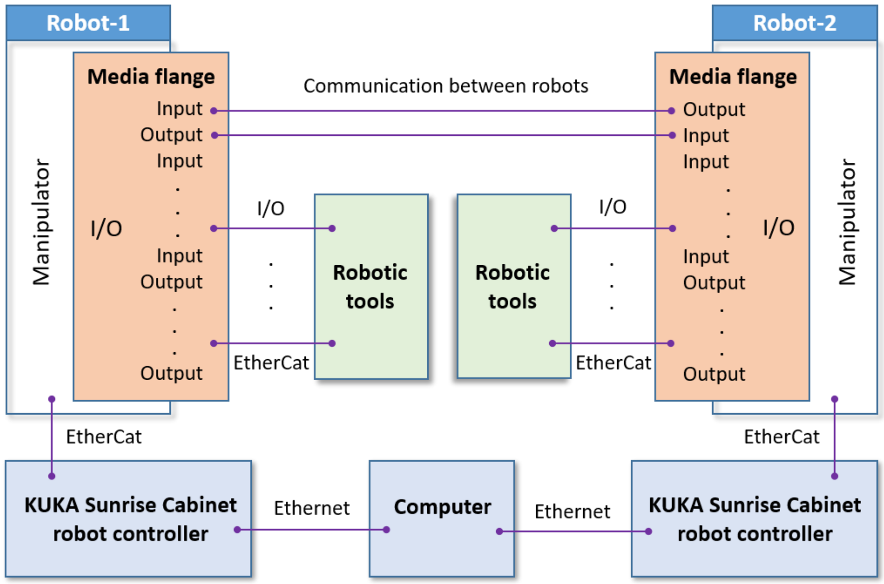

Fig. 3. Communication between hardware components.

3.1. Robotic System Architecture

As shown in Fig. 2, the proposed robotic system for disassembly uses two KUKA LBR iiwa industrial collaborative robots, Robot-1 and Robot-2. Thanks to its sensitive joint torque sensors as well as position and compliance control, the KUKA iiwa is able to work directly with humans within a shared workspace to achieve complex tasks safely (KUKA Roboter GmbH, 2016).

Depending on the disassembly tasks allocated to the robots, task specific tooling such as grippers, nutrunners, fixturing and clamping devices and tool changers could be utilised. Two KUKA Sunrise Cabinet controllers and KUKA smartPAD control panels are used to control the two robots. A development computer with KUKA Sunrise.OS software is utilised for configuration and programming.

3.2. Communication Between Hardware Components

Fig. 3 illustrates the methods of communication between hardware components in the cell. Robotic tools are installed on the media flanges of the robots and electrical inputs/outputs (I/O) or pneumatic interfaces are used for electrical power supply, communication (EtherCat) and compressed air connections.

Communication between the robots is realised by I/O, as shown in Fig. 3. Robot-1 could send a signal to Robot-2 using

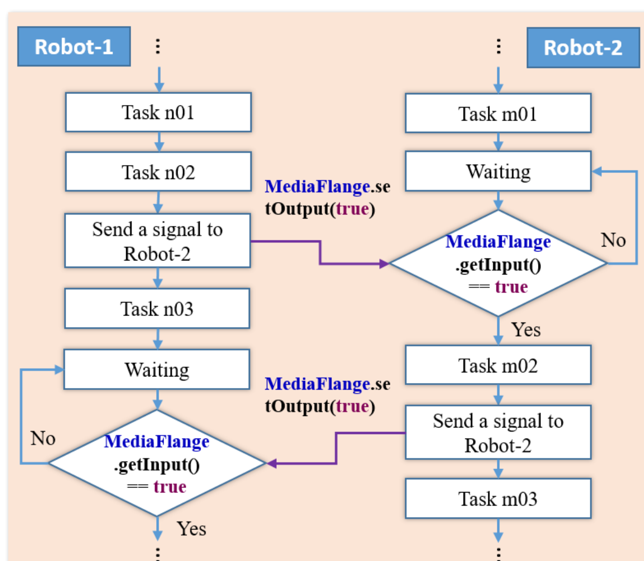

Fig. 4. An example of communication between Robot-1 and Robot-2.

its digital output and receive a signal from Robot-2 via its digital input. The I/O status can be changed to support disassembly process control. Fig. 4 is a flowchart illustrating the communication between the two robots.

3.3. Human-Robot Interaction

Previously reported interaction methods in HRC have included voice control (audio) and gestures (visual). However, the robustness and reliability of both these methods may be affected by ambient noise or variable lighting conditions in industrial environments (Maurtua et al., 2017). Instead, the proposed robotic disassembly cell uses contact (human touch) and position control for easy, reliable and effective human to robot communication. Joint torque sensors and an impedance controller make KUKA iiwa robots sensitive, compliant and able to react quickly to applied forces. The impedance control model can be considered as a virtual spring damper system (KUKA Roboter GmbH, 2016). The spring stiffness of the robot is configurable with ranges of 0 - 5000 N/m and 0 - 300 Nm/rad for translational and rotational degrees of freedom, respectively.

Table 1 shows an example of a touch function for human-robot interaction. The robot is waiting for the human operator to apply a downwards force (line 4). If the force is larger than the set value "f" in the negative direction of the Z-axis (line 7), the robot will execute the remaining program. Otherwise, it continues to wait. The set value in the negative direction of the Z-axis is chosen to avoid accidentally triggering a robot response.

Table 1

Touch function for human-robot interaction.

Input: value f of external force (set by the operator touching the robot)	
Output: next state	
1	**Function** Touch (f):
2	**Set** $i = 0$
3	**Get** current force value f_b on robot manipulator in Z direction
4	**Do** until $i = 1$
5	**Get** current force value f_c on robot manipulator in Z direction
6	**Find** force change $f_d = f_c - f_b$
7	**If** $f_d > f$ then
8	Set $i = 1$
9	**END If**
10	**END Do**

3.4. Human-Robot Task Allocation

Correct task allocation is critical for the effective organisation of disassembly work by the human operator and the robots to improve efficiency and productivity, and reduce the cost of production (Bänziger et al., 2018). In the proposed robotic cell, tedious, repetitive, heavy and hazardous disassembly tasks can be assigned to the robots. Tasks that require flexibility and adaptability are allocated to the operator. In addition, the operator performs disassembly tasks which would otherwise require specialist / expensive robotic tooling. Furthermore, the operator and the robots can work together on complex disassembly tasks.

A cost-effective subtask allocation strategy was developed for HRC using a genetic algorithm (Chen et al., 2014). A skill-based and dynamic task allocation approach was proposed for HRC (Müller et al., 2017). A trust-based task allocation for HRC was developed to optimise the subtask allocation between

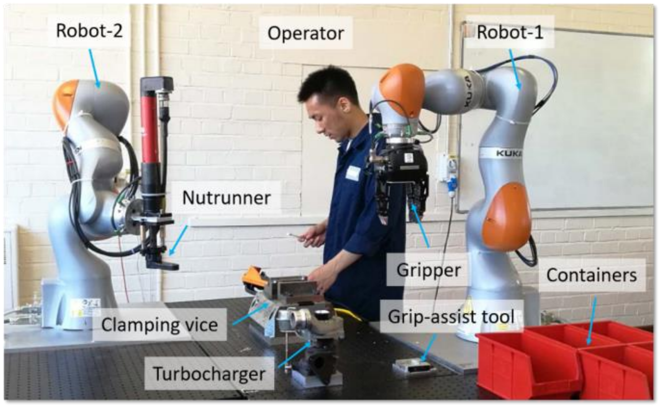

Fig. 5. Layout of the HRC disassembly cell.

human and robot (Rahman & Wang, 2018). Productivity, quality, human fatigue and safety can be used as evaluation criteria for HRC (Heydaryan et al., 2018). Average resource utilisation, mean flow time and investment cost could be utilised to select good quality task plans as opposed to poor quality ones (Tsarouchi et al., 2016). Average resource utilisation (ARU) is a ratio of the resource's "in-use" time over the "total time" required for the production (Tsarouchi et al., 2017).

Capabilities and ergonomics should be considered in task allocation (El et al., 2019). Continuous hard physical work is harmful to human health. A method was proposed for sequence planning considering human fatigue for human-robot collaborative disassembly (Li et al., 2019). A decision making framework was described for workplace layout generation and HRC task allocation to facilitate set-up or reconfiguration of an HRC workplace (Tsarouchi et al., 2016). Multiple criteria including shop floor space utilisation, total completion time and investment cost were used for human-robot task planning and human-robot workplace design (Tsarouchi et al., 2017).

In this research, the main aim of task allocation is to balance the activities of man and machines as far as possible while ensuring that both are assigned tasks according to their capabilities. Other relevant criteria for deciding task allocations include ergonomics, safety, investment cost, cycle time, and resource utilisation ratio.

4. Implementation and Case Study

To demonstrate the proposed human-robot collaborative disassembly cell, a case study was conducted in the authors' Autonomous Remanufacturing Laboratory, involving the disassembly of an automotive turbocharger. Two seven-axis collaborative robots (KUKA LBR iiwa 14 R820) with a payload of 14 kg and tools including a DC controlled nut-runner and electrical gripper were adapted to collaborate with the operator in disassembling the turbocharger.

4.1. HRC Disassembly Cell

Fig. 5 shows the layout of the HRC disassembly cell. A three-finger gripper (Robotiq, 3-Finger (Robotiq, 2020)) was installed on Robot-1 and a DC controlled nut-runner (Chicago Pneumatic, MC51 (Chicago Pneumatic, 2018)) was fitted to Robot-2 to unfasten the bolts. A pneumatic clamping vice (Schunk, TANDEM KSP-LH PLUS 250-IN (Schunk, 2020)) was employed to secure the turbocharger for disassembly. The vice was connected to and controlled by the media flange of Robot-1. A grip-assist tool was designed to work with the gripper to pick up the turbocharger and place it into the vice. The cell also has containers for storing dismantled components. The operator and the robots were able to work simultaneously on their individual or shared tasks. To achieve complex

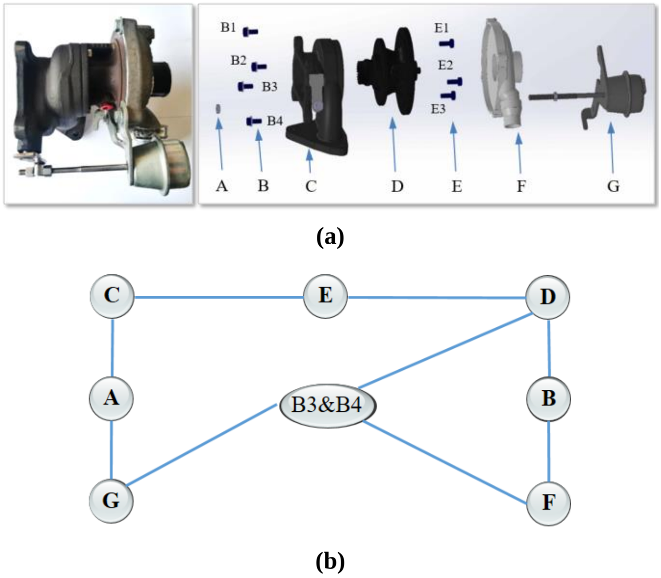

Fig. 6. An EoL automotive turbocharger: (a) exploded view and (b) connection diagram.

disassembly tasks, the human operator can collaborate with either or both of the robots. A safety laser scanner (not visible in Fig. 5) was employed to configure protection zones to ensure that the operator and the robots were not near the vice when it was powered.

The returned EoL turbocharger (BorgWarner 54359710029) is found in automotive vehicles including the Renault MODUS, Nissan NOTE and Dacia LOGAN. As illustrated in Fig. 6(a), the turbocharger components include a nut (A), four bolts (B, B1-B4) on the compressor housing, a turbine housing (C), a cartridge (D), three bolts (E, E1-E3) on the turbine housing (F) and an actuator (G). Fig. 6(b) shows the connections between the components of the turbocharger. The turbine housing (C) and cartridge (D) are connected by the three bolts (E). Bolts (B) connect cartridge (C) to the compressor housing (F). The actuator (G) is installed on cartridge (D) and compressor housing (F) by nut (A) and bolts (B3 and B4).

Table 2

Turbocharger disassembly task allocation involving Operator (O) and Robots (Robot-1 (R-1) and Robot-2 (R-2)).

No.	Tasks	O	R-1	R-2
1	Pick up the turbocharger and place it into the pneumatic vice		√	
2	Unfasten the bolt (B1) on the turbocharger			√
3	Put the bolt (B1) into the container		√	√
4	Unfasten the bolt (B3)			√
5	Put the bolt (B3) into the container		√	√
6	Support the actuator (G) to allow the unfastening of bolt (B4)		√	
7	Unfasten the bolt (B4)			√
8	Put the bolt (B4) on the table	√		√
9	Remove the nut (A) from the actuator (G)	√		
10	Put the actuator (G) into its container		√	
11	Unfasten the bolt (B2)			√
12	Put the bolt (B2) on the table	√		√
13	Separate the compressor housing (F) from the cartridge (D)	√	√	
14	Put the compressor housing (F) into its container		√	
15	Unfasten the bolts (E) from the cartridge (D)	√		
16	Separate and put the cartridge (D) into its container		√	
17	Put the turbine housing (C) into its container		√	

4.2. HRC Disassembly Task Allocation

The main tasks and the involved resources are shown in Table 2. Unfastening tasks are mainly carried out by Robot-2 with the electrical nutrunner. However, the unfastening task (Task 15) is assigned to the operator as the electric nutrunner on Robot-2 is unable to access the bolts (E). As a high level of flexibility is required, Task 9 is carried out by the operator. Although Robot-1 with a gripper has the ability to put the bolt (B4) on the table, Task 8 is allocated to the operator as Robot-1 can perform a parallel task (Task 6). In Task 13, impact forces are required to separate the compressor housing (F) from the cartridge (D). As impact forces can damage the robots, the operator uses a hammer to separate the compressor housing (F).

As depicted in Fig. 6, sequential disassembly and parallel disassembly are combined to make efficient use of resources, reducing disassembly time and cost. In sequential disassembly, one task is carried out after another, while in parallel disassembly, different tasks are performed simultaneously. Human-robot interactions and communications are presented in Fig. 7. As mentioned in Section 3.3, force control by touching is used for human-robot interaction to trigger the disassembly process and start Task 1. In addition, force control is employed to signal to Robot-1 to continue the disassembly operation after Task 9 and Task 15. Using human-robot interaction, the operator collaborates with Robot-1 to perform Task 13.

Note that the task sequence listed in Table 2 pertains to normal operating conditions. If difficulties arise that the robots cannot deal with, the operator will intervene. Once the operator has resolved the problem, the robots will continue their work.

Fig. 8(a) shows that the operator and robots work on

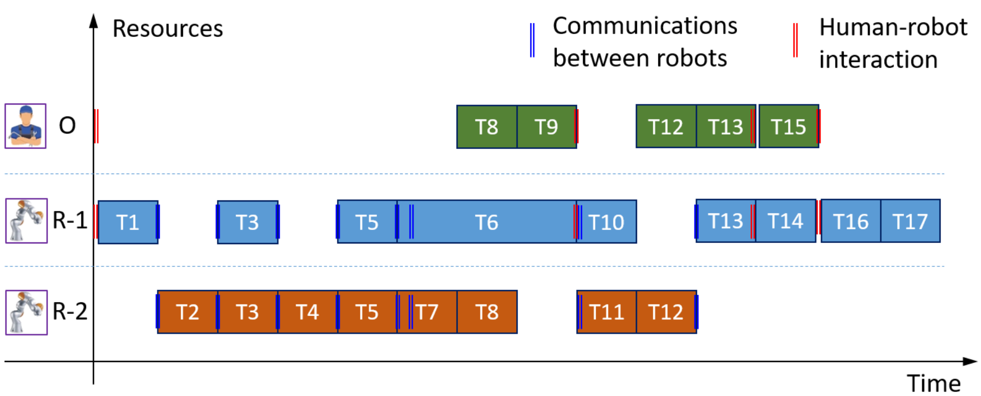

Fig. 7. Disassembly task sequence planning.

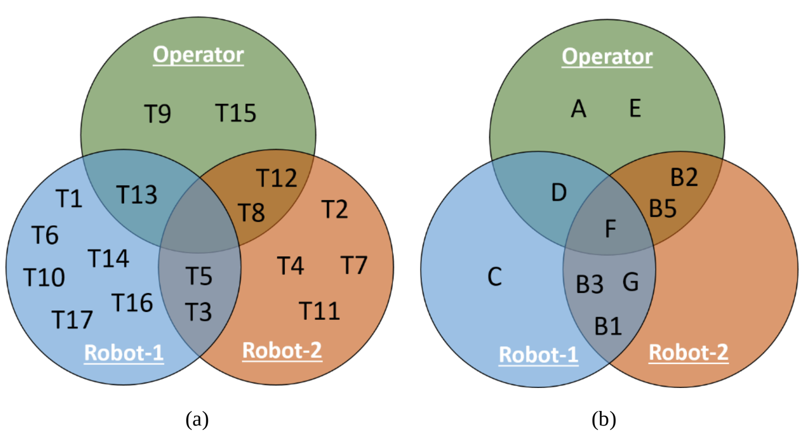

Fig. 8. HRC in the turbocharger disassembly process: (a) disassembly task allocation between operator and robots, (b) the resources involved in disassembling the turbocharger by component.

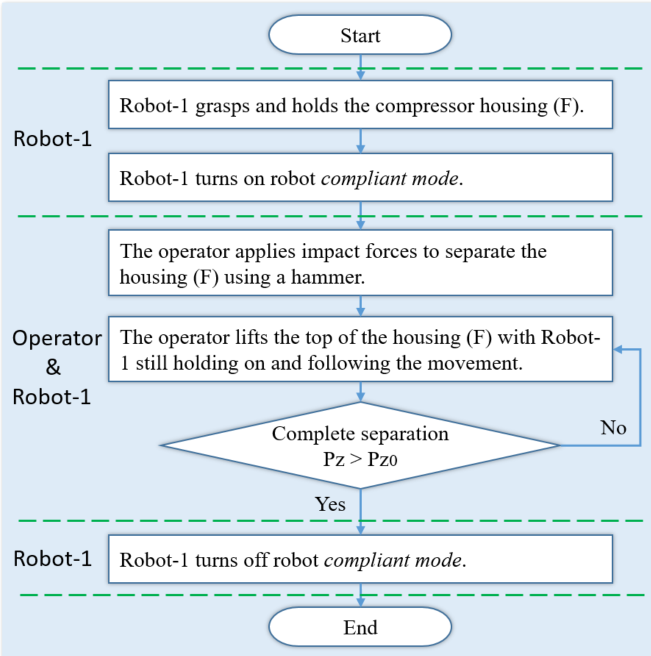

Fig. 9. Flowchart of task T13.

allocated disassembly tasks individually and collaborate on shared disassembly tasks. The operator works with Robot-1 to achieve the common task T13 and with Robot-2 for tasks T8 and T12. Tasks T3 and T5 are achieved using Robot-1 and Robot-2. The resources involved in dismantling the turbocharger are illustrated in Fig. 8(b). With the exception of parts A, C and E, the turbocharger is disassembled through collaboration between at least two disassembly resources. In addition, all resources are involved in the disassembly of part F.

4.3. *Collaborative Disassembly Procedure*

Active compliance control is implemented in the collaborative disassembly task T13, giving Robot-1 the flexibility needed to work together with the operator. The procedure for separating the compressor housing (F) from the cartridge (D) in task T13 is detailed in Fig. 9. First, Robot-1 moves its gripper to grasp the top of the compressor housing (F). Once Robot-1 has taken hold of the compressor housing, it turns on the compliant mode to enable the gripper passively to follow the movement of the housing in space. Next, the operator

Fig. 10. Photographs of the disassembly process: (a) force control to task T1, (b)-(k) the process and (l) the dismantled parts in containers.

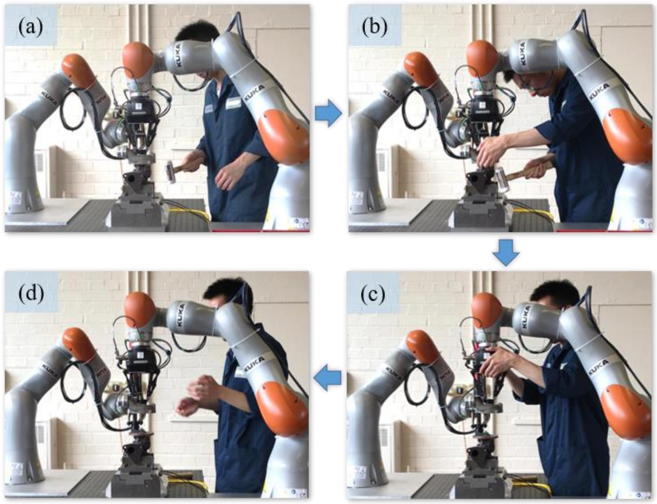

Fig. 11. Procedure of Task 13: (a) holding the compressor, (b) separating the compressor using a hammer, (c) lifting the compressor and (d) reaching the positional set position.

applies impact forces to separate the housing (F) using a hammer. Once the housing (F) is released, the operator lifts the top of the housing (F) with Robot-1 still grappling the housing following the operator's movement. Once the operator has moved the gripper to a positional set point, Robot-1 switches off its compliance mode and proceeds with the programmed task T14.

4.4. Results and Discussion

The Appendix gives the URL of the video showing the turbocharger disassembly operation. Fig. 10 captures the turbocharger disassembly process. To trigger the disassembly process, force control by touching was employed as shown in Fig. 10(a). Fig. 10(b) shows Robot-1 holding the turbocharger using a bespoke grip-assist tool in Task 1 and Fig. 10(c) shows Robot-2 unfastening the bolt B1 in Task 2. Robot-1 picks up the bolts B1 from Robot-2 in Task 3 (Fig. 10(d)). As depicted in Fig. 10(e), Robot-1 supports the actuator in Task 6 to allow Robot-2 to unfasten the bolt B4 in Task 7. Next, the operator picks up the unfastened bolt B4 from Robot-2 (Fig. 10(f)). The operator removes the nut (A) in Task 9 (Fig. 10(g)). Fig. 10(h) shows Robot-1 putting the actuator into its container in Task 10, while Robot-2 unfastens the bolt (B2). The operator unfastens the bolts (E) in Task 15 (Fig. 10(i)). Finally, Robot-1 picks up and puts the turbine housing (C) in Task 16 (Fig. 10(j)) and the cartridge (D) in Task 17 (Fig. 10(k)) into their respective containers. Fig. 10(l) shows the disassembled parts.

Fig. 11 illustrates the procedure of Task 13 to separate the compressor housing (F) from the cartridge (D) using HRC. Robot-1 grasps and holds the compressor and turns on the robot compliant mode (Fig. 11(a)) to allow the operator to knock the compressor housing (F) out using a hammer (Fig. 11(b)). Then, the operator lifts the compressor with Robot-1 still holding onto the compressor and following its movement (Fig. 11(c)). Finally, the disassembly task ends when the gripper on Robot-1 reaches the set position (Fig. 11(d)).

The process time and disassembly sequence are shown in Fig. 12. The facility "in-process" time ($T_{in\text{-}process}$) is given by:

$$T_{in-process} = \sum_{i=1}^{n} T_i \quad (1)$$

where T_i is the completion time of task i allocated to the operator or to a robot, and n is the total number of tasks. The facility cycle time (T_{cycle}) could be estimated using the following equation:

$$T_{cycle} = T_{in-process} + T_{waiting} \quad (2)$$

where $T_{waiting}$ is the sum of the waiting time given by:

$$T_{waiting} = \sum_{j=1}^{n-1} T_{wj} \quad (3)$$

Table 3
Cycle time data of disassembly resources.

Resources	Cycle time	"In-process" time	Waiting time	"In-process" time ratio
Operator	102s	84s	18s	82.3%
Robot-1	245s	166s	79s	67.8%
Robot-2	136s	115s	21s	84.6%

In Eq. 3, T_{wj} is the waiting time between tasks j and ($j+1$) assigned to the operator or to a robot, and n is again the total number of tasks.

The total cycle time of the disassembly process is 245s, as shown in Table 3. Considering the waiting time between the disassembly tasks, the facility "in-process" time ratio ($R_{in\text{-}process}$) could be calculated using the following equation:

$$R_{in-process} = \frac{T_{in-process}}{T_{cycle}} \quad (4)$$

The obtained facility "in-process" time ratios are shown in Table 3. Considering the idle time in the disassembly process, the resource utilisation ratio (R_{RU}) could be calculated as:

$$R_{RU} = \frac{T_{cycle}}{T_{total-cycle}} \quad (5)$$

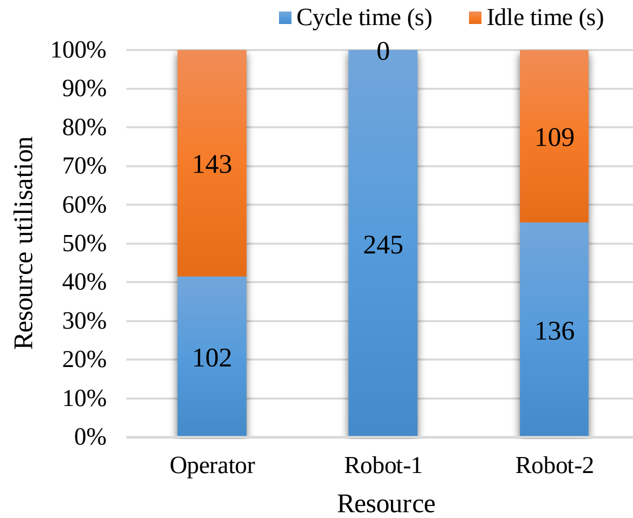

Fig. 13. Resource utilisation ratio.

Table 3 shows that the in-process time ratio of Robot-1 is low. However, from Fig. 12, it can be seen that the total idle time of Robot-1 is made up of short waiting periods during which the robot cannot perform any other tasks. Thus, for Robot-1, it could be concluded that the task allocation could not be further improved. On the other hand, despite the waiting time for the human operator being quite short (18s), it could be usefully employed for quick inspection or error recovery activities to ensure that the disassembly process is carried out smoothly.

As shown in Fig. 13, the resource utilisation ratios for the

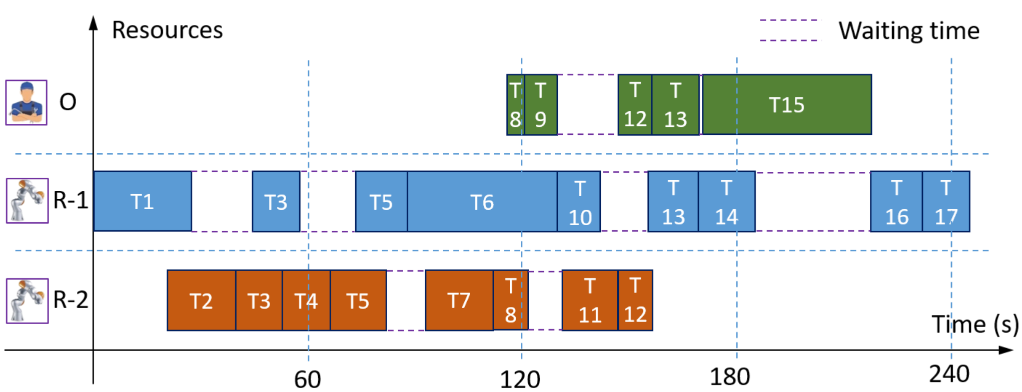

Fig. 12. Time of disassembly tasks.

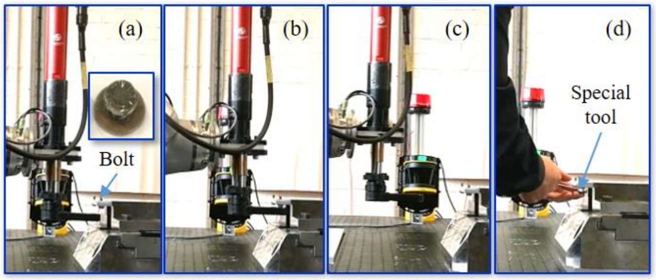

Fig. 14. Demonstration of strategy for error recovery (a) Robot-2 approaches the bolt to be removed, (b) Robot-2 fails to remove the bolt, (c) Robot-2 leaves and calls the operator, and (d) the operator intervenes using a special tool to remove the bolt.

operator, Robot-1 and Robot-2 are 41.6%, 100% and 55.5%, respectively. The total cycle time of the disassembly process could be further reduced and the resource utilisation ratios could be increased by optimising the task allocation and increasing the motion speed of the robots. Alternatively, the operator and Robot-2 could be used to service another suitably positioned and laid out disassembly cell to increase their resource utilisation ratios. The cell could be speeded up by increasing the robots' motion speed and screw unfastening speed.

The human operator provides the higher degree of flexibility and adaptability required to handle disassembly uncertainties. Fig. 14 gives an example showing the flexibility of the cell. When the robot could not handle the disassembly of a damaged bolt (Fig. 14(a)) and the tool was slipping after engaging with the head of the bolt (Fig. 14(b)), the robot called the operator (Fig. 14(c)) to handle the bolt with a special tool (Fig. 14(d)).

Preliminary trials show that the proposed HRC disassembly cell with two collaborative robots is able to take an automotive turbocharger apart in approximately four minutes using HRC. Work is being carried out to improve the demonstration cell by adding robotic tools and functionalities, such as tool changing, part recognition using a vision system, and human-robot task allocation with dynamic sequence planning.

5. Conclusions

The main barriers to achieving automated disassembly are uncertainties in the quality and unpredictability in the frequency of returned EoL products and the resulting variance in the required disassembly processes. An effective strategy is to use a semi-automated cell as human-robot collaborative disassembly can deal with these issues by combining the respective strengths of manual and robotic disassembly, increasing flexibility and productivity and reducing capital cost.

This paper has presented a new experimental cell for human-robot collaborative disassembly based on two robots and a human operator. The cell was designed for use as a test bed for the development and validation of robotic disassembly strategies and technologies as well as the demonstration of the disassembly of small products such as automotive water pumps and automotive turbochargers. Collaborative robots were employed to work with the operator in a shared environment without the need for safety fencing. Digital I/O was adopted for communication between the two robots. Human-robot interaction was realised using force and position control. Active compliance control was utilised to achieve complex disassembly HRC tasks. A case study has been detailed that has demonstrated the successful application of the proposed cell for the dismantling of a turbocharger. The case study has shown that the proposed HRC cell has the potential to provide a flexible and adaptable solution to disassembly compared with a fully automated disassembly cell, and could release people from tedious and repetitive work when compared with a manual cell.

In the future, we will enhance the cell with additional tools and capabilities, including a tool changer for increased functionality and a vision system to enhance the cognitive ability of the robot, enabling it to collaborate more effectively with the operator. Human-robot task allocation methods are being developed to make full use of resources and reduce disassembly time and cost. These methods will take account of ergonomic factors to ensure the health and safety of operators and increase their efficiency. In addition, a systematic approach will be developed to deal with disassembly uncertainties. Digital twin technology will be developed and implemented for processes such as disassembly product analysis, disassembly sequence planning, robotic cell design, and disassembly process simulation.

Appendix

The case study described in Section 4 can be viewed at

https://www.youtube.com/watch?v=kOwGe_LbLzs .

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