Human-Robot Cooperation in Disassembly: A Rapid Review

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Abstract: Despite the evolution of autonomous systems, manual disassembly of electrotechnical devices persists due to the limitations associated with product variability. Effective cooperation between humans and robots is essential to overcome the constraints of disassembly. This article presents a literature review focusing on human-robot cooperation in disassembly, with the aim of summarizing existing research, identifying gaps, and defining possible contributions. The state of the art includes methodologies for product representation, task allocation between a human and a robot, and task scheduling optimization. Efficient cooperation would integrate human adaptability, robot efficiency, and direct communication, to anticipate disassembly actions to prioritize the well-being and involvement of the human at every stage of the process.

1 INTRODUCTION

Nowadays, the growing quantity of electronic waste is a major challenge. The disassembly complexity of these devices has an indicative impact on the environment and the economy. Despite the need for many tasks to be carried out, manual disassembly persists, affecting workers' health and operational efficiency. Humans have difficulty facing the workload imposed and the inherent difficulty of disassembly tasks. At the same time, even though autonomous systems are evolving, their use in disassembly is limited by product variability (Hjorth et al., 2022). This product variability requires a flexible and adaptable system. With the respective limits and advantages of the agents, cooperation between human and robot would offer possibilities for dealing with the constraints encountered in manual disassembly and that with fully automated systems. The question to be resolved is how to ensure efficient cooperation between human and robot, while encouraging the attractiveness of this new approach. This article proposes a literature review focusing on human-robot cooperation intended to roboticists, automaticians and the human sciences in the context of disassembly. It aims to summarize the work that has been done and to highlight current gaps, with a view to highlighting our contribution and guiding our study.

2 LITERATURE REVIEW

2.1 Methodology for a Review

The rapid review, conducted using the SCOPUS database and providing an accelerated synthesis, aims to outline interactions among various agents, particularly in cooperative contexts, and to review disassembly methods and planning. Focusing on disassembly and human-robot cooperation, we combined these keywords to form the basis of our research:

disassembl* AND (cooperati* OR collaborat*) AND ((human AND robot) OR allocat*)

- Disassembl*: Focus on research and studies on the disassembly process and its issues.
- Cooperati* OR Collaborat*: Include work that considers aspects of cooperation between different agents, detailing how they interact and mutually support each other in a shared work environment. The term "collaboration" in robotics can be synonymous with "cooperation" in automation.
- (Human AND Robot) OR Allocat*: Focus on the relationship between humans and robots, and on the way in which tasks are allocated between these two agents.

Before analyzing the titles and abstracts of documents obtained, inclusion and exclusion criteria are defined (Table 1).

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Table 1: Inclusion and Exclusion Criteria.

Inclusion Criteria	• Publication Year: From 2014 to 2024 • English language • Document type: Conference paper, Article, Conference Review, Review
Exclusion Criteria	Subject areas not related to our research • Physics and Astronomy • Business • Management and Accounting • Chemical Engineering • Chemistry • Biochemistry • Genetics and Molecular Biology • Neuroscience

Research from the last 10 years until today has been taken into account, excluding fields not related to the research topic. Furthermore, only the document types "Conference Paper", "Article", "Conference Review" and "Review" available on SCOPUS have been included, thus excluding papers relating to books. After that, a review of the titles and abstracts allowed us to select only a limited number of articles that seemed relevant to our question concerning the efficient use of human-robot cooperation in disassembly. A complete analysis of the texts is then carried out, and a synthesis is presented, outlining the state of the art on the subject of disassembly and cooperation, as well as the methods used to allocate disassembly tasks.

2.2 Results of Execution

A keyword search on SCOPUS allows us to visualize 153 documents. Eleven documents from external sources were added, which enabled us to familiarize ourselves with the subject and which met the inclusion and exclusion criteria (Table 1), finally making it possible to study 164 documents in total. After applying inclusion and exclusion criteria, and removing duplicates, 106 documents remained to be analyzed, based on titles and abstracts. In the end, 41 documents were studied, some of which were excluded after text analysis (Fig. 1).

3 STATE OF THE ART

The methodology employed in disassembly efficiency improvement, as seen across literature, typically comprises three steps: product representation for task sequencing, task allocation based on predefined criteria for human or robot involvement, and task scheduling optimization using algorithms. This chapter is thus structured accordingly to represent these steps.

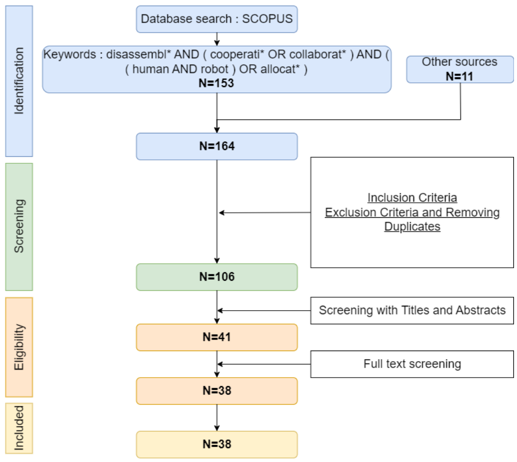

Figure 1: Rapid review.

3.1 Disassembly

In an era where technology is evolving, the quantity of electrotechnical waste is growing rapidly. Disassembling these products is part of the circular economy for their end-of-life treatment. This process has the advantage of extending the life of equipment and maximizing its value while reducing the environmental and economic impact of the constant production of electrotechnical products (Lee et al., 2020b; Li et al., 2019; Vongbunyong et al., 2017; Huang et al., 2019; Wu et al., 2024). However, the question is how these products can be disposed of. The following points can be noted up to now (Table 2).

Defining product end-of-life could help to define the tasks to be executed during disassembly. This disassembly could be destructive or non-destructive, and it would be easier to identify until which subassemblies and components should be extracted. Guo et al. (2023) went further, proposing partial destructive disassembly by representing the degree of degradation of the product at end-of-life. These end-use scenarios influence the disassembly process and the methods used to recover components. In this way, methods are proposed for classifying products and representing them, so that the disassembly sequence can then be determined. End-of-life products can be represented using AND/OR graphs (Fang et al., 2023; Xu et al., 2020a; Chu et al., 2023; Lou et al., 2024; Parsa et al., 2021), oriented graphs (Lee et al., 2020b; Jungbluth et al., 2017; Liao et al., 2023; Lee et al.,

Table 2: Product management.

Group	Product Management	Papers
Requalification	Maintenance, Reuse, Repairs, Remanufacturing	Hjorth et al. (2022), Li et al. (2019), Huang et al. (2019), Wu et al. (2024), Ding et al. (2019), Jungbluth et al. (2017), Sartori and Schlette (2021), Buhl et al. (2019), Liao et al. (2023), Fang et al. (2023), Chen et al. (2023), Prioli and Rickli (2020), Chen et al. (2022), Xu et al. (2020a), Xu et al. (2020b) Guo et al. (2023), Chu et al. (2023), Lou et al. (2024), Huang et al. (2021), Belhadj et al. (2022), Lee et al. (2022)
Take-back and Waste treatment	Recycling, Recovery, Proper disposal	Lee et al. (2020b), Wu et al. (2024), Ding et al. (2019), Jungbluth et al. (2017), Liao et al. (2023), Fang et al. (2023), Chen et al. (2023), Prioli and Rickli (2020), Chen et al. (2022), Guo et al. (2023), Chu et al. (2023), Lou et al. (2024), Huang et al. (2021), Lee et al. (2022), Chatzikonstantinou et al. (2019), Liu et al. (2023), Yuan et al. (2023), Lee et al. (2020a), Parsa et al. (2021), Renteria et al. (2019)

2020a), priority and constraint disassembly matrices (Li et al., 2019; Xu et al., 2020b; Belhadj et al., 2022) or vision systems for product recognition (Vongbunyong et al., 2017; Ding et al., 2019; Bdiwi et al., 2017). These representation methods are used to identify the disassembly sequence.

Considering that two agents are going to cooperate together to perform these tasks, it is necessary to determine which agent should be assigned which task. In this way, a classification of tasks is established (Antonelli et al., 2019), generally by evaluating their difficulty, and the variability of products introduces challenges in task execution, necessitating adaptive strategies. It is also possible to group products and their components in a class diagram, according to their characteristics (Jungbluth et al., 2017). This class diagram can also be completed by the data set of the disassembly cell (Prioli and Rickli, 2020).

3.2 Human-Robot Cooperation

Despite the manual predominance of disassembly, cooperation aims to improve efficiency by valorizing human flexibility, dexterity, and knowledge, combined with the precision and repeatability of robots (Matsas et al., 2017). In the context of this cooperation, several authors propose to classify tasks according to their difficulty (Liao et al., 2023; Xu et al., 2020a,b; Lou et al., 2024; Parsa et al., 2021), in order to finally determine if the task can be performed by the human, the robot or both. However, it is necessary to take into account the capabilities and skills of the human, as well as their needs and preferences, in order to keep the human at the center of the process and promote the acceptability of this approach. A list of the added values of each agent involved in the process has been established based on a study of the literature (Table 3). For example, Chen et al. (2022) examined the impact of robot use on ergonomics and human workload, demonstrating the benefits of the robot for these purposes and emphasizing the importance of understanding how humans work with the robot.

On the one hand, table 3 confirms the human advantages in terms of physical and cognitive performance, as well as his/her added value in terms of the adaptability required by the complexity of disassembly tasks. The robot, on the other hand, is highlighted for its operational and economic performance, as well as the comfort it brings to humans in terms of safety and reduced health risks. Nevertheless, it is easy to see that more positive points emerge from the use of the robot. It is therefore possible to envisage the implementation of weighting criteria in our future studies, based on the most important added values and enabling us to gain efficiency.

To ensure the acceptability of human-robot cooperation, safety measures must be taken. In particular, it is proposed to predict the intentions and gestures of the robot and the human to make cooperation safer and more transparent (Hjorth et al., 2022; Liu et al., 2023, 2019). Tian et al. (2023) go a step further, proposing motion prediction that takes uncertainties into account. The advantage lies in the fact that ”robots can react earlier based on the knowledge of the human behavior provided by the prediction model” (Liu et al., 2023). Furthermore, visual recognition, including methods such as point cloud recognition and instance segmentation, allows the robot to be guided by human actions, enabling it to acquire new skills and improve its performance (Vongbunyong et al., 2017; Chen et al., 2023; Renteria et al., 2019; Bdiwi et al., 2017; Duan et al., 2023). To prevent disturbing noise and light conditions, Huang et al. (2021) proposed interaction via tactile contact, force and position control. In such an environment, knowledge and skills need to be managed. Databases and graphs can be created to ensure the acquisition, availability, and sharing of skills between the two agents (Ding et al., 2019). The integration of active compliance control, as proposed by Huang et al. (2019) and Huang et al. (2021), enables the robot to adapt dynamically to variations and constraints encountered during product handling, thus enhancing the precision and efficiency of human-robot cooperation. The robot autonomy could be further enhanced by equipping it with the knowledge and skills of an

Table 3: Added Values of Humans and Robots.

	Human	Robot	Papers
Adaptability, Flexibility	+	-	Hjorth et al. (2022); Vongbunyong et al. (2017); Huang et al. (2019); Belhadj et al. (2022); Duan et al. (2023); Liu et al. (2019); Li et al. (2019); Jungbluth et al. (2017); Liao et al. (2023); Xu et al. (2020a,b); Guo et al. (2023); Huang et al. (2021); Belhadj et al. (2022); Parsa et al. (2021); Mateus et al. (2018)
Cognitive, Decision Making, Learning, Identification	+	-	Huang et al. (2019); Jungbluth et al. (2017); Prioli and Rickli (2020); Lou et al. (2024); Huang et al. (2021)
Complexity, Uncertainty, Unpredictable	+	-	Hjorth et al. (2022); Huang et al. (2019); Wu et al. (2024); Jungbluth et al. (2017); Liao et al. (2023); Guo et al. (2023); Huang et al. (2021); Lee et al. (2022); Yuan et al. (2023); Parsa et al. (2021); Liu et al. (2019)
Cost, Economy	-	+	Li et al. (2019); Vongbunyong et al. (2017); Huang et al. (2019); Jungbluth et al. (2017); Xu et al. (2020a,b); Guo et al. (2023); Belhadj et al. (2022); Yuan et al. (2023); Parsa et al. (2021)
Dexterity, Sensory motor	+	-	Huang et al. (2019, 2021); Liu et al. (2019)
Efficiency, Time, Speed, Precision	-	+	Li et al. (2019); Huang et al. (2019); Liao et al. (2023); Xu et al. (2020a,b); Guo et al. (2023); Belhadj et al. (2022); Duan et al. (2023); Liu et al. (2019); Prioli and Rickli (2020); Huang et al. (2021); Bdiwi et al. (2017); Mateus et al. (2018); Lee et al. (2022); Parsa et al. (2021)
Effort, Endurance, Fatigue, Stress	-	+	Li et al. (2019); Jungbluth et al. (2017); Lou et al. (2024); Bdiwi et al. (2017); Liu et al. (2019); Tian et al. (2023)
Ergonomic, Health, Workload	-	+	Li et al. (2019); Jungbluth et al. (2017); Chen et al. (2022); Lou et al. (2024)
Hazardous, Safety	-	+	Wu et al. (2024); Huang et al. (2019); Liao et al. (2023); Prioli and Rickli (2020); Huang et al. (2021); Lee et al. (2022); Yuan et al. (2023); Renteria et al. (2019); Duan et al. (2023); Mateus et al. (2018)
Payload, Power, Strength	-	+	Huang et al. (2019); Jungbluth et al. (2017); Sartori and Schlette (2021); Huang et al. (2021); Liu et al. (2019); Mateus et al. (2018)
Monotony, Patience, Tedious, Repeatability	-	+	Liao et al. (2023); Renteria et al. (2019); Bdiwi et al. (2017); Liu et al. (2019); Li et al. (2019); Huang et al. (2019); Sartori and Schlette (2021); Xu et al. (2020b); Lou et al. (2024); Huang et al. (2021); Yuan et al. (2023); Parsa et al. (2021); Duan et al. (2023)

informed software agent. This would be based on the product model (Jungbluth et al., 2017). Data management can also be carried out via a Cloud space, bringing together real-time disassembly information. In particular, it connects all the agents involved in the process, capturing human and robotic inputs to share, diffuse, and combine the knowledge and capabilities of each agent. Finally, this information is used to distribute tasks in real-time (Prioli and Rickli, 2020).

Again to improve acceptability, and after evoking proposals for knowledge sharing and motion prediction, Alhaji et al. (2021) explored trust factors, such as reliability, dependability, perceived predictability, and confidence. Indeed, ”trust is the foundation of successful human collaboration” (Alhaji et al., 2021). These factors are examined to enable adaptation of the robot’s dynamic behavior. Once again, to improve robot capabilities, working with a robot with two arms will not replace the work of the human, but will improve robot flexibility, dexterity, and the safety of disassembly operations (Buhl et al., 2019). However, defining a robot’s capabilities in advance is challenging due to their dependence on the use case, application, and specific robot.

Additionally, it is essential to take into account the variability of humans and the products handled. Human factors, such as skill level, cognitive load, and physical condition, vary from one individual to another and can have a significant impact on the efficiency of human-robot cooperation. Some research has already addressed the issue of human fatigue, by incorporating models of human fatigue into optimization algorithms for disassembly planning (Li et al., 2019). The integration of an HMI as an assistant to the human could facilitate robot programming, control, and agent coordination while offering a disassembly sequence. In this respect, Sartori and Schlette (2021) proposed developing a digital twin to represent the robot and its interactions and include human actions. In this way, the aim is to have a digital representation of what will be physically executed.

3.3 Task Allocation

In the context of human-robot cooperation in the disassembly process, optimization techniques are used to allocate tasks between these two agents. The aim is to maximize process efficiency while taking into account various resource and safety criteria and constraints. For this purpose, various algorithms have already been developed and tested in the literature (Table 4).

Mathematical models optimize the disassembly sequence, aiming to minimize the total execution time with constraints such as transition times, safety, resource availability, and precedence rules (Lee et al., 2022; Antonelli et al., 2019). These criteria (time, safety, complexity) can also be grouped together in a utility function to maximize overall utility (Liao et al., 2023). Recently, metaheuristics have become more

Table 4: Optimization algorithms.

Population-based meta-heuristics	Method	Criterion	Papers
Swarm Intelligence	1. Bees Algorithm 2. Bees Algorithm 3. Bees Algorithm 4. Particle Swarm Optimization 5. Grey Wolves Optimization	1. Time, Human fatigue 2. Profit, Energy Consumption, Difficulty, Number of workstations 3. Time, Cost, Difficulty 4. Time with position-related and task assignment constraints 5. Profit, Complexity, Ergonomics, Time	1. Li et al. (2019) 2. Xu et al. (2020a) 3. Xu et al. (2020b) 4. Chu et al. (2023) 5. Lou et al. (2024)
Evolutionary computation	1. Genetic Algorithm 2. Genetic Algorithm 3. Global Search - Multi-objective evolutionary algorithm	1. Time, Cost 2. Non-targeted component index, Time, Operator change 3. Makespan (Time), Cost with task assignment constraints	1. Guo et al. (2023) 2. Parsa et al. (2021) 3. Chatzikonstantinou et al. (2019)

commonly used, with particular emphasis on the use of the bee algorithm. This algorithm has been particularly promoted in recent years for the quality of the solutions it produces, its greater convergence and diversity, and its faster execution time, compared with other algorithms such as the genetic algorithm, the grey wolf algorithm, and modified teaching-learning optimization (Xu et al., 2020a,b). However, table 4 shows that these methods are often limited to minimizing time and cost. The complex problems encountered in the disassembly process would require a reflection on the chosen criteria, representing more the difficulties encountered by the human, such as workload, and those encountered during disassembly execution, such as variability. The advantages of cooperation could then be put to the fore.

For example, Belhadj et al. (2022) proposed to take human adaptability and efficiency into account with the generation of disassembly plans. For this, an inference engine assigns operations to the robot if there is no interference with the human. Based on the total disassembly time and the part wear, several solutions are thus proposed until the end of disassembly, with the advantage of leaving a certain amount of flexibility in the decision-making process for the execution plan. In order to retain the strengths of each agent and divide tasks as effectively as possible, according to a sharing mode that gives the human a degree of autonomy throughout execution, Mateus et al. (2018) proposed a study of manual disassembly to decompose tasks into movements. The compatibility and suitability of resources is then assessed by moving from a qualitative to a quantitative description (time, part, process). This approach then enables an allocation range to be established, with greater emphasis on the strengths of both agents. Faced with the vulnerability and risks associated with the uncertainty of disassembly tasks, Yuan et al. (2023) go one step further by proposing an assessment of resilience, taking into account stability, redundancy, efficiency, and adaptability. Thus, by visualizing resilience indexes, rational decision-making can be made in the allocation of tasks between the human and the robot. While some talk about adaptability, Lee et al. (2020b) proposed a finite-horizon optimization problem, based on the principle of a predictive control model. This minimizes cost by taking into account human and robot movements during task execution.

These complementary approaches enrich the field by offering solutions tailored to the specific needs of disassembly processes, while highlighting the importance of considering a diverse range of methods for task allocation, taking into account process efficiency and quality, human fatigue and safety. While some are trying to optimize the allocation of tasks between two agents within the same work cell, others are seeking methods to balance entire disassembly lines, primarily aimed at reducing the number of workstations, improving the fluidity of the load between different humans, and reducing production time (Wu et al., 2024).

3.4 Discussions

While significant advances are being made in the management of end-of-life electrotechnical products and in human-robot cooperation for disassembly, gaps remain. Product diversity requires adaptive and optimal management, with analytical approaches to guide disassembly decisions. Algorithmic task allocation optimizes efficiency while taking into account resource and safety constraints, but needs to incorporate more criteria to reflect problem complexity and human willingness. The integration of human variability is envisaged for his/her ability to adapt and make decisions in variable and complex situations. Involving humans right from the decision-making phase is crucial for a more social approach to disassembly, valuing their skills and combining them effectively with those of the robot. The development of decision support systems is promising for gathering, sending and supporting humans. To improve the efficiency and acceptability of this cooperation, it is essential to accurately assess the skills required for each task, and to foster direct communication between humans and robots.

- H1: Defining product end-of-life, taking into account its variability, makes it easier to identify the disassembly sequence.
- H2: Involving humans right from the decision phase to determine the allocation of tasks, by combining their specific skills with those of the robots, helps to identify an optimized allocation of functions.
- H3: Optimized allocation of disassembly tasks between the human and the robot, taking into account a wide range of relevant criteria such as human flexibility, maximizes the efficiency of disassembly operations.
- H4: A more precise assessment of the skills required for each task, and the encouragement of a direct exchange between human and robot, will enhance the attractiveness and human well-being.

4 COOPERATION FRAMEWORK

4.1 Definition and Application Proposal

To ensure the efficiency of human-robot cooperation and encourage its attractiveness, it is proposed to involve the human in task allocation and planning decisions from the outset. A decision support system would support this process, providing real-time feedback and enabling the human to use his/her skills effectively, within his/her own limits. In this way, it is possible to define the know-how-to-operate and know-how-to-cooperate of both the human and the robot for the execution of disassembly tasks. Principles for evaluating ”Know-How-to-Operate” functions (KHO) and ”Know-How-to-Cooperate” functions (KHC) of agents guide the assignment of tasks to the Human, the Robot, or both. KHO concerns the ability to analyze and make decisions on the process, while KHC is the ability to communicate, to decide task allocation and build a model of the other agent. Based on these assessments, it will be possible to allocate functions. In other words, ”levels of autonomy can be identified for each capability of each agent, and the combination of the levels of each agent defines the levels of cooperation” (Pacaux-Lemoine et al., 2023). On the one hand, it is crucial to highlight the importance of human adaptability in dealing with product variability. On the other hand, robots play a crucial role in enhancing efficiency and alleviating the human workload.

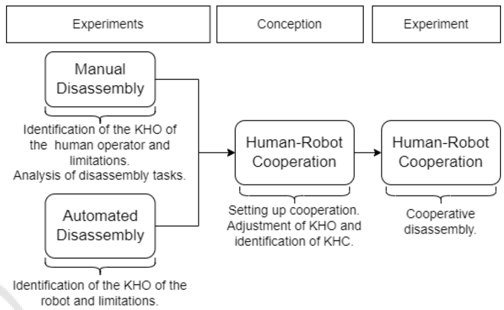

Figure 2: Methodology.

Before setting up human-robot cooperation and testing it through experiments, it is planned to test manual disassembly on the one hand, and automated disassembly on the other (Fig. 2). The aim is to assess the efficiency, added values of each approach, as well as to evaluate the disassembly tasks and their difficulty.

4.2 Expected Results

Manual disassembly aims to assess the analytical skills of humans and their effectiveness in disassembly tasks, highlighting adaptability, cognitive abilities, dexterity, and flexibility. The analysis at this stage also includes the tasks performed, the tools used, and the difficulty and skills required for each task. For automated disassembly, it is crucial to identify robot capabilities and limitations, focusing on communication with the human and tasks that support human work.

To take the added values of human and robot (Table 3), we expect automated disassembly to be faster and more efficient than manual disassembly, due to the precision and repeatability of robots. However, manual disassembly could offer greater flexibility and adaptability to face product variability. The results of this experiment will provide useful information on the advantages and limitations of manual and automated disassembly. These data can be used to guide the decisions to be made when developing human-robot cooperation. The aim is to take into account the skills and limitations, wishes, and well-being of the human, so as to keep him/her at the center of the process and make his/her work more attractive after the addition of the robot.

5 CONCLUSIONS

Although this rapid review has its limitations as a preliminary overview, this paper addresses the persistent problem of manual disassembly of electrotechnical devices, despite advances in autonomous systems. Efficient and optimized human-robot cooperation is crucial to overcome the challenges associated with disassembly tasks. A rapid review of the literature, focusing on human-robot cooperation in disassembly, examines 38 articles, exploring the latest methodologies. Products are generally represented by graphs or matrices, enabling a disassembly sequence to be defined. Tasks are then allocated according to task difficulty and agent skills. Other proposals are put forward to ensure safe and efficient cooperation. In addition, several studies focus on optimizing planning and task allocation. Although this article focuses on metaheuristics, future research could explore neural networks and reinforcement learning. By identifying current gaps and outlining future research approaches, our aim is to steer human-robot cooperation strategies toward maximizing operational efficiency and satisfying human needs. Efficient cooperation would combine the adaptability and cognitive abilities of humans with the efficiency and assistance of robots to lighten the workload of disassembly tasks. Human involvement at every stage of the process is crucial to progress towards social robotics. With this in mind, it is useful to analyze both the human and the robot in disassembly tasks before implementing cooperation. Future research will build on this initial approach by continuing the bibliographic monitoring to ensure a comprehensive understanding of the evolving landscape of human-robot cooperation in disassembly tasks.

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