INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.274

Design for robotic disassembly

Lykke Margot Ricard ✉, Emilie Folkmann, Lars Carøe Sørensen, Sofie Bach Hybel, Roberto de Nóbrega and Henrik Gordon Petersen

University of Southern Denmark, Denmark

✉ lmri@iti.sdu.dk

Abstract

This study envisions a unified paradigm for design for automated disassembly. The goal is to integrate disassembly insights related to precious material recovery with the design phase for sustainable lifecycle management.Targeting plastic products with embedded electronics, the collaboration between design and robotic engineers aims to program a robot for disassembly for the LEGO® motor (45603) as demonstration, emphasizing a disassembly map as a vital tool. By considering the limitations and strengths of robots, this research pioneers a design for disassembly framework.

Keywords: *design for x (DfX), design automation, computer-aided design (CAD), product design, circular economy*

1. Introduction

One of the strategies in the circular economy is to reuse critical or rare materials in order to reduce the material resources used in product manufacturing. High resource consumption is an environmental problem (Stahl, 2016; Lieder and Rashid, 2016). Lifecycle assessment studies of various types of electronic waste show that the efforts of high-quality collection and recycling outweigh the environmental burdens of irresponsible disposal (Baxter et al., 2016), and that even small amounts of critical metals and precious minerals are vital for the overall environmental accounts of value chains (Mathieux, et al. 2017). Remanufacturing includes a focus on such rare earth elements as neodymium magnets, critical metals, expensive chips, and circuit boards, which could potentially be recovered from end-of-life electronics and used in new products. While ISO standards (ISO 14001, 2015) address environmental management systems, there are no established remanufacturing feedback systems for component design (Hochwallner et al. 2022). The absence of such a feedback system can limit the pool of viable candidates for remanufacturing and concomitantly cause economic and environmental value loss. Moreover, scholars in sustainable manufacturing have argued that remanufacturing as an end-of-life strategy needs to be considered early, during product design, to reduce lifecycle costs and the environmental footprint (Badurdeen et al., 2018).

Design for disassembly holds the potential to recover or mine components of high value from electronic products at the end of their user phase. The paper envisions a unified paradigm for design of automated disassembly. The goal is to integrate disassembly insights of precious material recovery into the design phase for sustainable lifecycle management. The study presents the early findings from a research experiment called Design for Disassembly funded by Innovation Fund Denmark as part of TraCE, the Danish national partnership for circular economy. The experiment targets plastic products containing electronics. Since the electronics are hidden, they also represent a hidden value in products (i.e. toys). Baldé, Yamamoto, and Forti (2023) estimate that humans throw away nine billion kilograms of hidden e-waste worldwide every year, which represents a recycling value of ten billion US dollars. Manufacturing new products with old parts can be one of the keys to green conversion success in manufacturing. In this experiment, robot engineers and design engineers are working together in the Industry 4.0 lab of the University of Southern Denmark (SDU) to program a robot to disassemble and free up target components for reuse. However, this is not as straightforward as one might think. Firstly, the task of disassembling products for remanufacturing is riddled with challenges, primarily because the original design choices often impede non-destructive disassembly, e.g. the use of irreversible fasteners or component connections that lead to destructive disassembly, which affects the reusability of components. Secondly, used products will often have varying conditions of wear and tear, which require an agile setup that can quickly be reconfigured and programmed in order to automate the disassembly process. A robotic solution can be designed to meet such agility and automation requirements. Robots provide system flexibility, and they remain relatively easy to program. Moreover, robotic manipulators are known for their high accuracy and repeatability. Nonetheless, the amount of manual programming and adjusting must be kept at a minimum for remanufacturing to be feasible and safe. Industrial robotic arms are interesting because they can handle large quantities of products, allow cost reduction, and are not burdened by tedious repetitive tasks. Incorporating the limitations and strengths of robots, this research pioneers a design for a disassembly framework.

The paper is structured as follows: First an introduction is provided to explain the motivation behind the research. This is followed by a review of related work to frame and differentiate the experimental study. Next, the creation of a disassembly map is presented that serves to bridge the designed 3D product architecture of a LEGO® Education Medium Angular Motor (product number 45603) with robotic disassembly. The robotic demonstration is then outlined, based on the initial segment of the disassembly map, with focus on harvesting a ferrite magnet embedded in a plastic casing. Finally, the paper concludes by discussing the usefulness of the design tools for robotic programming and outlining future directions.

2. Related work from the science base

Prior to the year 2000, there were some preliminary efforts in automation design, but not until approximately 2012 had the momentum behind the area truly surged, marking a decades-long scientific tradition in product assembly within manufacturing (Dario et al., 1994). A search for related work on the utilization of robotic disassembly tasks for recovery or remanufacturing was conducted using the databases Web of Science and Scopus. The findings indicate that articles on robotics consider disassembly tasks as viable possibilities for recovery of raw materials, particularly when tasks are either semi-automated or fully robotized. The variable input for disassembly compared to the fixed input for assembly is what complicates the automation (Bogue, 2007). Lee et al. (2011) identifies three design trends as the cause for increased complexity in automatic disassembly being 1) products and materials are becoming more complex and heterogeneous, 2) product are becoming smaller and sleeker, and 3) more proprietary fastener systems are being developed. Scholars who have explored the improvement of the disassembly process through design include Favi et al. (2019), Mandolini et al. (2018), and Bogue (2007). Their research emphasizes how simple design rules concerning material compatibility, product architecture, and the selection of fasteners and joint connectors play a role in the implementation of a design for disassembly concept.

Another relevant concept is the human-robot collaboration, which addresses the need for effective and efficient disassembly line balancing, and considers such factors as profit, time, and energy expended. While there is a shared emphasis in the literature on optimizing the industry for ease of disassembly, repairability, or re-manufacturability through automated processes, the current body of literature predominantly provides programmable product scores and reviews of existing technology. From our search for recent related work, the following studies stand in relation to defining the maturity of the technology. One is a feasibility study by Marconi et al. (2019), who propose a robotic system for disassembly of electronics to recover valuable components for a reuse- or remanufacturing scenario. The aim of their study is to validate the performance of the system using printed circuit boards (PCB) as the use case and targeting disassembly of microprocessors soldered onto them. Their work cell is built using a two-axis manipulator as the robotized gripper, a revamped wave soldering machine to desolder the microprocessors and a central unit for coordinating motions. In the experimental tests they succeed in disassembling 450 reusable microprocessors from 50 printed circuit boards by combining the two machines. Their disassembly system is limited, however, in that the current setup is only automated for a single PCB model. To further develop the work cell for more variance in incoming products, they point to the need to develop vision systems for the machine to recognize the type of PCB and an automatic tool exchange system to mount different grippers depending on the type of PCB.

In a recent study, Engelen et al. (2023) builds upon exactly this research gap in developing the robotic technology to handle the significant variations expected in products' condition from post-consumer products. Like Marconi et al. (2019), Engelen et al. (2023) point to both multi-functional tooling and specialized disassembly tooling as a necessity in order to program the robot for shifting operations. They state that robotic motion programming must be able to disassemble various fasteners between components, which requires substantial programming time, specific knowledge, and skills. In the Engelen et al. (2023) study, they program a robot's movements through manual guiding by a human to overcome the expensive and highly skilled programming requirements needed for multi-functional tooling and variable operations. For future research they stress the need to include an intuitive teaching method for complex motion operations in disassembly (i.e., grasping, removing, and sorting the disassembled components). The study highlights a need for a data warehouse where each robotic motion can be stored as a skill, so that they can be used independently of the location of parts or fasteners with identical recognition points.

Also the Hochwallner et al. (2022) study addresses the considerable variations in volume and product types in emphasizing the importance of human-robot interaction in remanufacturing. In contrast to guiding robots through diverse disassembly tasks, their remanufacturing system streamlines the process by automating certain manual tasks, allowing human operators to focus on cognitively demanding aspects. They showcase a successful implementation in automating a specific automotive part and associated processes This approach enhances efficiency by delegating repetitive, non-ergonomic, and hazardous tasks to robots while leveraging human expertise for intricate decision-making in remanufacturing tasks. The case study involves applying a sealant to a lid assembly covering electronic components. They apply a stepwise process of 1) identifying one or more potential processes to change from manual to automated disassembly, 2) showcasing an automated disassembly, and 3) testing if the bill of process could be set up for automation.

The final study in this review is Lu et al. (2020), who focus their study on new optimization techniques to account for both manpower and electricity consumption. They describe how the problem of balancing the disassembly planning between the use of energy and the recovered profit could be accommodated by solving the Profit-Oriented and Energy-Efficient Disassembly Sequencing Problem (PEDSP). Due to the recurring challenge of variance in end-of-life products, they underscore the necessity for a predictive model assessing subassembly quality. In their study, they use a ball point pen and an electronic radio as cases to create a disassembly AND/OR graph that illustrate the relationship between the subassemblies, fasteners, and disassembly tasks. The graphs are applied in planning the disassembly paths and the definition of which parts are left for reuse or recycling. They find that the varying quality directly affects the potential for recovered value, but also the time it takes to complete the recovery through disassembly actions.

To conclude the review, the robotic technology for disassembly is not yet fully developed nor is there established remanufacturing feedback systems (Hochwallner et al., 2022) that the design of products can feed into. Commonly addressed in the literature is the fact that the use of robotics in disassembly use cases does not effectively handle significant variations in products that stem from diverse fastener usage, fluctuating volumes, and end-of-life conditions. Sundin et al. (2012) build upon these challenges and point to the necessity of including design features that enable end-of-life processes. This paper therefore focuses its attention on design for robotic disassembly that aims to integrate disassembly insights into precious material recovery into the design phase for sustainable lifecycle management.

3. The disassembly map

Leveraging two design methodologies drawn from the existing literature on original products' repairability, the bridge between the fields of design engineering and robotics can be established. The first method involves mapping the product architecture to a planned and optimized disassembly sequence, using the disassembly map by De Fazio et al. (2021). The second method, proposed by Mandolini et al. (2018), provides a time-based optimization for the disassembly sequence of a product. Both scholars have a clear focus: to develop a method to measure and decrease disassembly time for selective disassembly. They state and list several other methods, where the objective is to minimize the number of disassembly actions in the disassembly sequence or to reduce the number of components to remove.

The disassembly map by De Fazio et al. (2021) is a method for visualising the architecture of a product and the disassembly actions and sequence required. It incorporates considerations such as the forces involved, the type of tools used, and the connections disassembled during manual disassembly. The map provides a comprehensive overview of the disassembly process. However, it presents only one perspective of the disassembly which may not align with the objective of the disassembly process. It may not be necessary to perform total disassembly and map the complete product disassembly; therefore, De Fazio et al. (2021) provide explicit guidance on selective or modularized disassembly, aiming to enhance economic feasibility.

The adaptation of the method for this study does not account for the disassembly time of the disassembly actions, nor of the product disassembly. The main issue on how to implement disassembly time meaningfully into the decision stages of product development stands unanswered. Therefore, the disassembly map is constructed starting with design engineers manually conducting a total disassembly of a product and documenting the process, aiming to minimize the sequence of actions steps. Although total disassembly is rarely the goal, it facilitates dialogue in order to select target components and materials. This is the primary objective of this initial disassembly. The selection of components to recover must strike a balance between the complexity of the disassembly, environmental responsibility, and economic gain. The disassembly map inherently includes information about the subparts of the product, known as the Bill of Materials (BoM), the disassembly process, referred to as Bill of Process (BoP), and the required tools, designated as Bill of Tools (BoT). With the manual disassembly map complete, along with the CAD-files and the BoT, a discussion between design and robotics engineers can be conducted in order to understand the product architecture and devise the robotics disassembly map. This entails mapping the interdependencies between components, which dictate the order of disassembly actions in order to accomplish the least destructive path to each target component. Identifying high-priority components in the disassembly map provides a clear objective for planning the robot's path to the target parts. These must be harvested while trying to minimize the number of steps, energy usage and damage to the components marked for reuse.

Another key aspect to consider, for both manual and automated disassembly, is whether there are clusters that could be targeted instead of individual components. Opting for a selective disassembly approach enables opportunities for strategic and controlled destruction in order to reduce the number of disassembly steps and overall disassembly time. For instance, accepting the destruction of components destined for recycling rather than those intended for reuse could be a viable strategy.

A current limitation is that there is no interface between the disassembly map and the robotics software. Therefore, the design data needs to be input manually. In addition, comparing the disassembly map with the capabilities of a robotic solution may highlight discrepancies, since tasks that are easy for humans may prove challenging for robots and vice versa. Similarly, considerations for required tools must be adjusted to accommodate robotic arm movement and available tooling options. To address these challenges, the original method has been extended in order to incorporate a planned disassembly sequence tailored for robotic cells. This includes the utilization of a robotic manipulator, a Universal Robots UR5e, finger grippers for end-of-arm tooling, a finger exchange system, a Dremel and a fixture setup using pneumatic linear actuators for the case product chosen, a LEGO® Education Medium Angular Motor (product number 45603). Furthermore, the robotic disassembly map must outline the planned actions described in coordinates.

The disassembly map of the planned demonstration for robotic disassembly of the case product can be viewed in Figure 1.

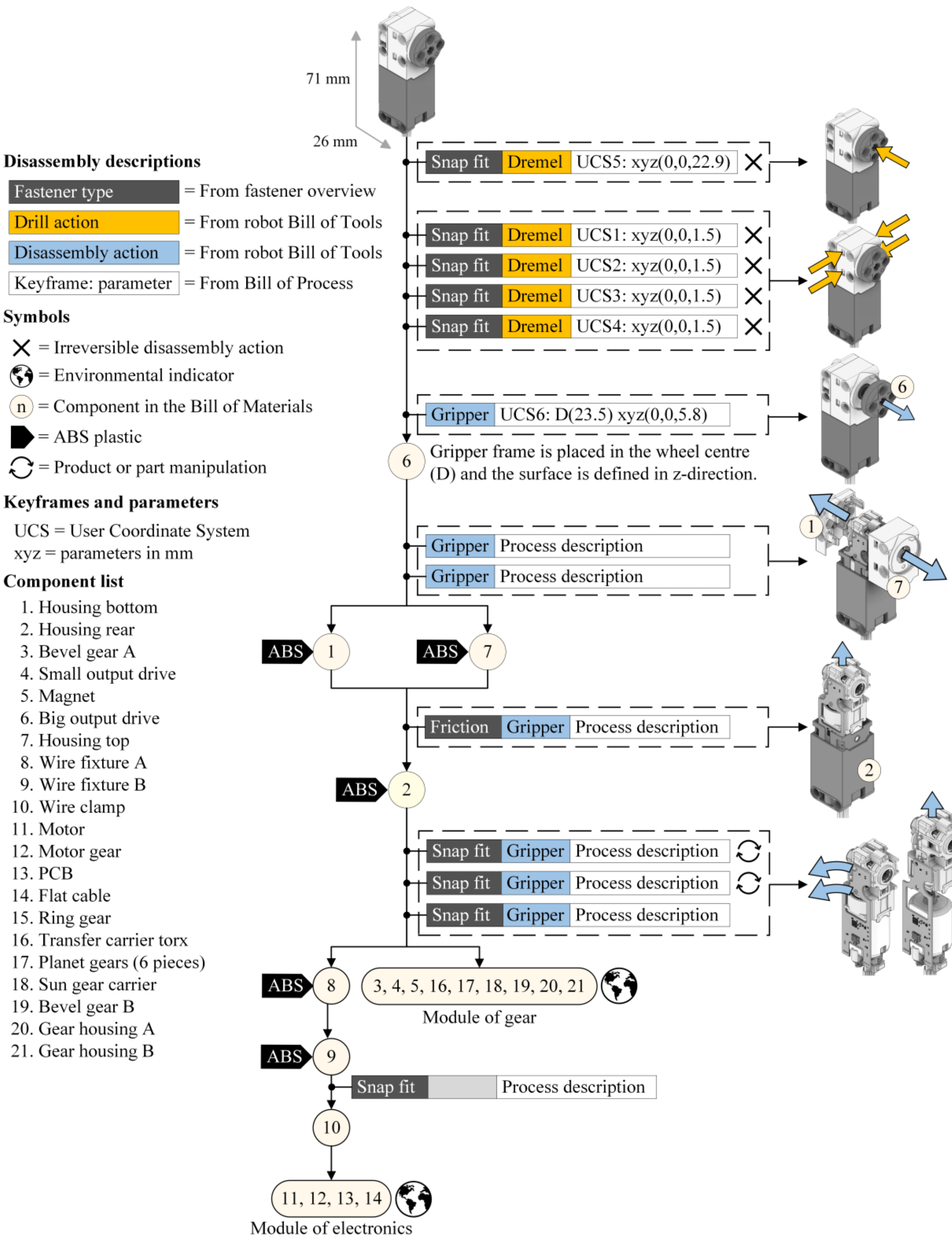

Figure 1. A disassembly map prepared for robotic disassembly

4. The robotic demonstrator

The robotic demonstrator setup comprises a UR5e robotic manipulator equipped with a ROBOTIQ gripper that incorporates a pneumatic attachment system for tool exchange. The selected tools for the disassembly of the LEGO® motor are, a Dremel with a 4 mm drilling bit and a set of 3D printed custom fingertips, and finally, the system including fixtures to secure the tools and a more complex custommade fixture with pneumatic linear actuators to keep the case product in place for the disassembly process, as shown in Figure 2.

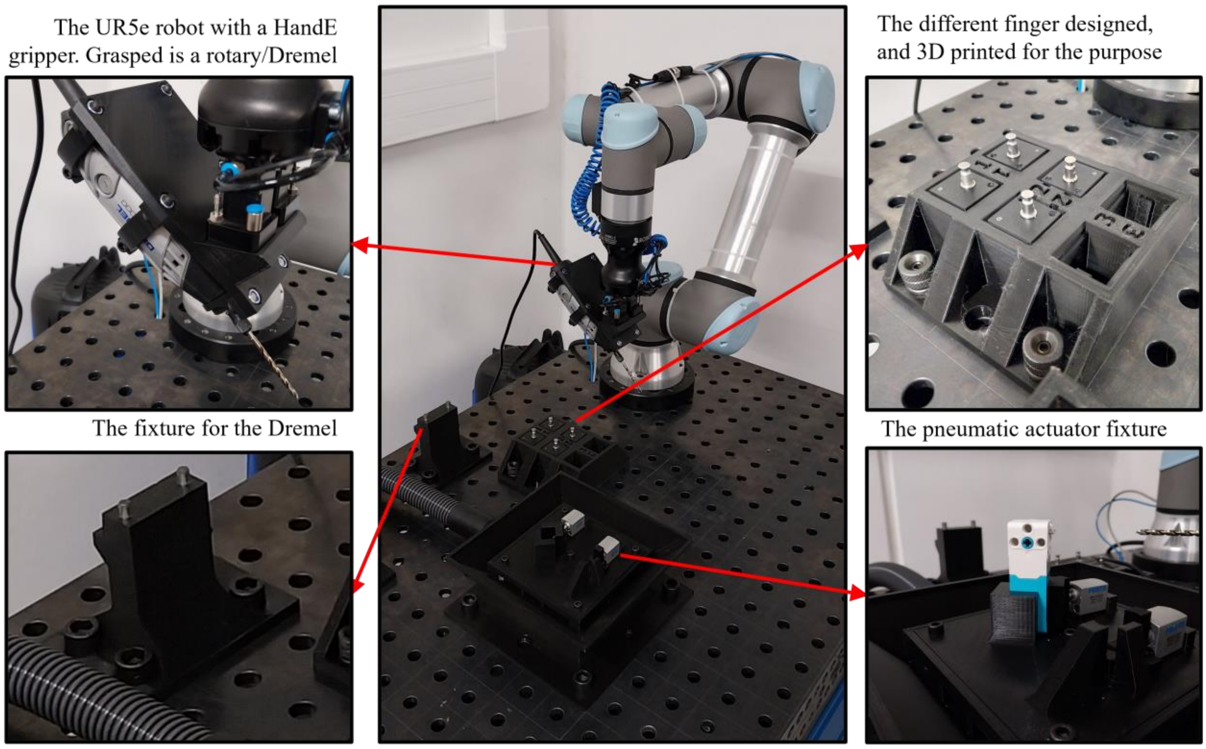

Figure 2. Robotic demonstrator

The robotic disassembly map is based on the demonstration setup, where the initial part of the map is dedicated to a drill-out process to destroy five strong snap-fits that encapsulate the upper housing and the wheel of the LEGO® motor. This initial process is illustrated in Figure 1, with the indication of the required tool and respective location of the action. Even though the full automated disassembly map has been projected, for this experiment, only the initial five steps relating to the drilling and removal of the wheel and the upper casing was executed on the physical platform in order to increase the development speed of a practical proof-of-concept. In contrast to the manual disassembly map, incorporating keyframes from the 3D CAD software is necessary to define the start and stop positions for the robotic actions. This disassembly map facilitates the planning of robotic disassembly sequences, enabling time estimation for each action. Given the time estimate of each action, cost, and energy usage estimation can be calculated (Ramírez et al., 2020). Actions can then be strategically planned to take into consideration: 1) Product geometry; 2) Direct routes; 3) Sequence shortcuts; 4) Minimizing destruction of components with plausible reuse potential; 5) Targeting clusters rather than individual components to minimize action steps, and 6) Preventing damage and cross-contamination of target components e.g. from leakages from batteries, capacitors, or similar components.

By exporting the frame data in the format of an XML file, it can become input to a custom-designed program that will extract and translate the data for the robotics programming tool. This step converts the 3D data into code, which will be used by the robot to perform the planned sequence. The process of converting the data should be streamlined to avoid unnecessary complexity and time consumption. Whereas a plug-in for direct conversion and extraction of the data would be convenient, , an intermediary translation program will be sufficient for demonstrations purposes.

The data points are imported from the design CAD program into the robotics programming tool to be executed on the I4.0 lab demonstration platform. After the drill tool has been picked up, the robot proceeds to perform the first action step. This is shown in Figure 3, where the drill action starts in the outer work frame and is then executed linearly towards the inner work frame. In this process, the snap-fit is removed, unlocking the blue wheel. Subsequently, the drill is retracted linearly to the outer work frame while spinning, a measure taken based on manual testing in order to prevent the wheel from grabbing onto the drill bit.

The robotic manipulator then moves to a finger exchange station to change from the drill to gripper fingers. Thereafter, the robot removes the wheel using the same approach. Leveraging extracted CAD data, the robot is equipped with the necessary knowledge of the diameter and centre point of the wheel, enabling the robot to grasp and remove the wheel accurately. In this study, the robot performs the first five actions in the robotic disassembly map for the LEGO® motor as the case product. As depicted in Figure 4, a strong snap-fit mechanism obstructs the release of the ferrite magnet (component no. 5 in Figure 1), which could be targeted as a high-priority component.

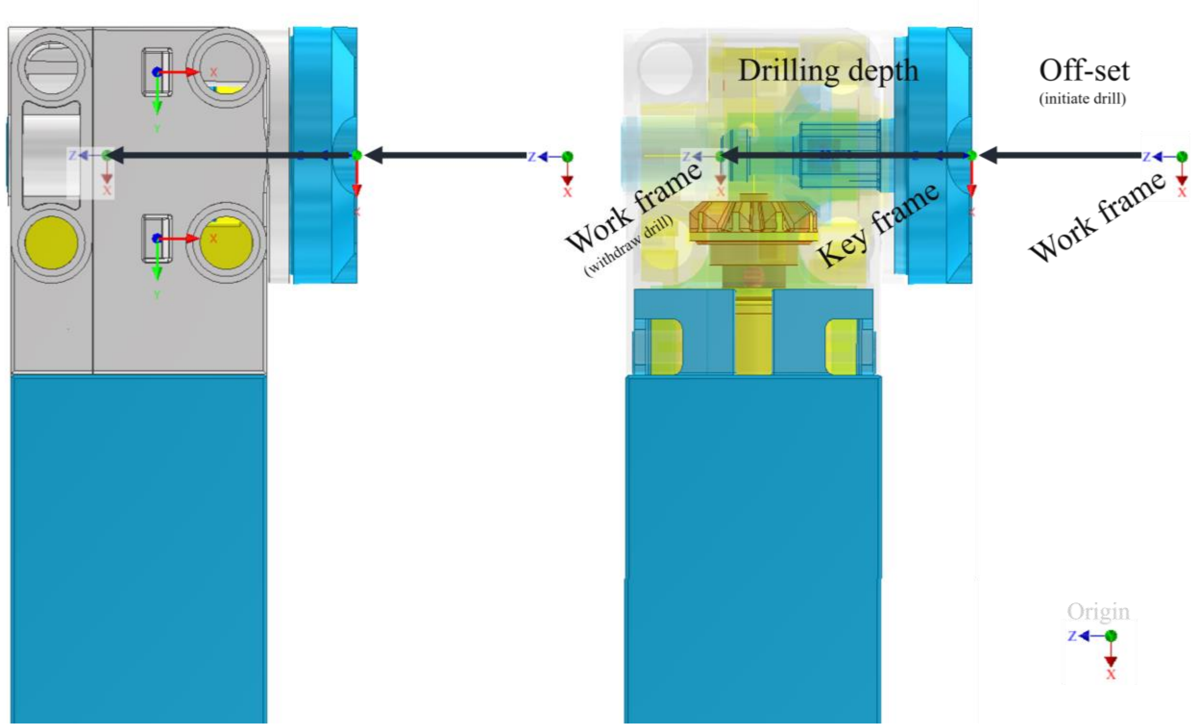

Figure 3. The planned action for the robot to drill

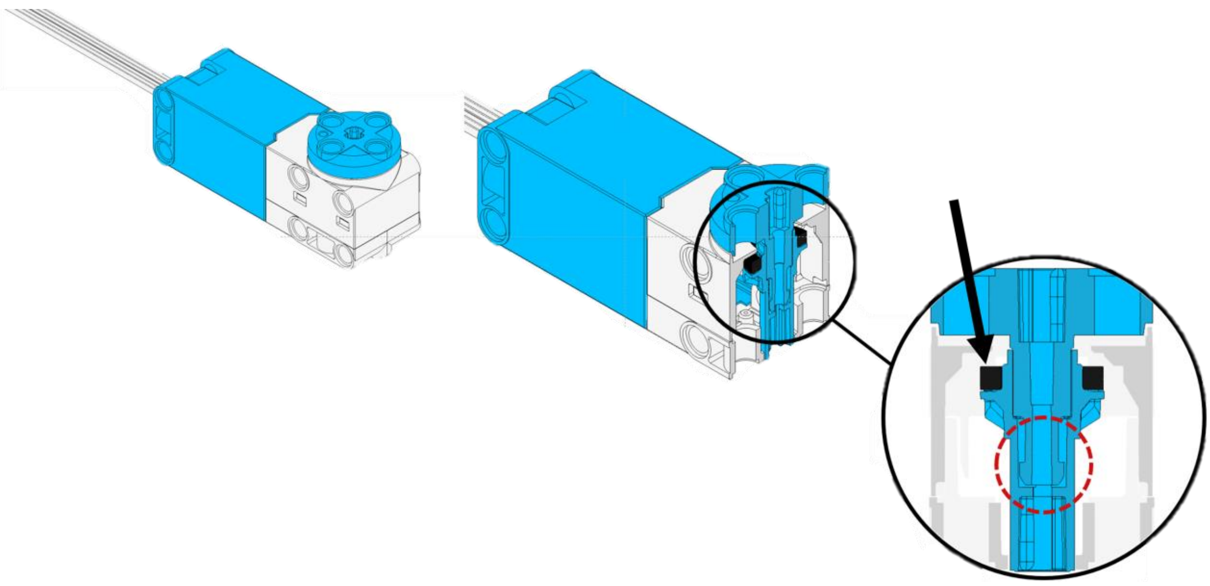

Figure 4. A strong snap-fit blocking the release of the magnet

5. Results and discussion

5.1. Design tools for robotic disassembly

CAD information for dismantling products, especially old products, is typically limited. This limitation means that defining all the required actions may not be easily accomplished using CAD programs alone. It has been proposed to use kinaesthetic teaching to program the robotic setup (Engelen et al., 2023). This is because such an approach enables operators with limited knowledge within the robotics domain to do the programming. The approach is excellent for bootstrapping programming of relatively simple tasks. We argue, however, that the approach is often infeasible for complex disassembly processes, particularly if the batch size of a specific product is relatively small or if there is a significant variation in the condition of the products (a scenario of low volume and high variations). This scenario will require the operator to interact with or teach the robot – perhaps – too frequently. While feedback from an operator on how to perform a specific action on a particular product could be valuable, enabling automated disassembly on a larger scale should minimize human interference as much as possible. Therefore, the programming of the robotics setup should primarily rely on CAD information. Such information can for instance be described in a digital passport.

The CAD information can be split into two categories. The first category contains traditional 3D model data about the products. The second category overlays this with additional information that describes the actions to perform the disassembly along with the parameters needed to initialize the chosen action. The additional information can either be added to the existing CAD data, or alternatively, a more effective approach would be to integrate it as an inherent part of the product design process. Our approach is to use the extended CAD information together with the disassembly maps to describe how the disassembly process should be performed.

Figure 5 summarizes the 2-step design approach on how to enable easy robotics programming. The first step is to include the additional information in the traditional CAD model data. As an example, consider a product with a snap-fit and that this snap-fit must be drilled out to perform the disassembly. Then the additional data would state that a drill action should be used. The location of the snap-fit and the drilling depth can directly be obtained from the CAD model data. Based on the extended CAD information and the chosen disassembly map, the bill-of-process, bill-of-material, and bill-of-tools can then be exported automatically. These three bills are used by the custom translation software to automatically generate and initialize the robotics program. Additional robotic information may be required to complete the robotics program.

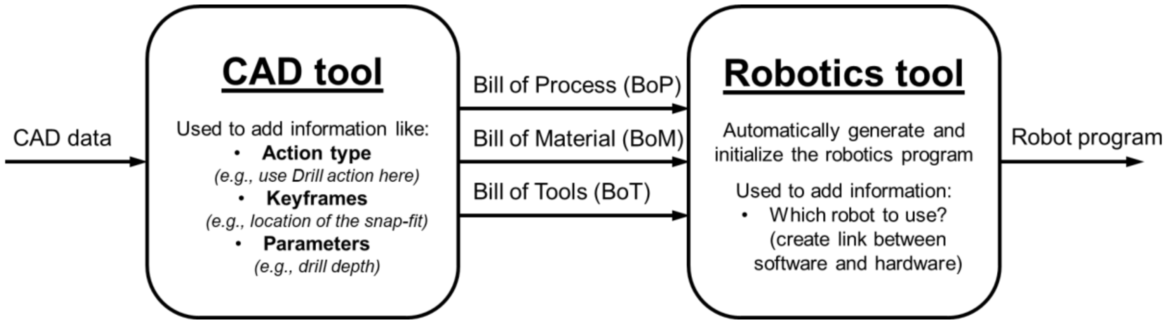

Figure 5. Data flow

5.2. Innovation opportunities from developing the automation technology

Automating high-volume assembly tasks is readily achievable, and the applicability has only expanded with the introduction of robot manipulators. Automating low-volume assembly productions, however, is still challenging today, since it requires that the automation solution can be quickly reconfigured to be economically feasible. The need for flexibility is even larger when addressing disassembly tasks, where even the same type of product can arrive in varying conditions. To overcome such challenges, easy and automated programming is required as well as the possibility for automatic adaptability. Manual programming must also be kept at a minimum. In relation to robot programming, a concept known as digital twin is being used, which includes a digital representation of the physical assets. The digital twin enables bi-directional data flow between the control software and the physical assets, which empowers effortless robotics programming. As an example, programming the robot can be carried out using a simulation while robot position or paths are taught by moving the physical robot. The digital twin can also be used to log the state of the system. For instance, measuring the time a certain tool has been engaged should be a straightforward task for a cyber-physical system.

The following points have been identified as essential for the automation of disassembly: 1. Implementing the entire approach and testing it on the disassembly of various products, and 2. Exploring the variations in the disassembly process when the conditions of the product change. Practical strategies to enhance the success rate would involve employing computer simulations and leveraging data obtained from analogous tasks.

5.3. Re-design opportunities

The disassembly map is found to be a valuable design tool for aligning the product architecture with the planned disassembly sequence. This method integrates seamlessly with a data-driven approach, which is crucial as society moves towards robotic implementation. In simpler terms, it serves as a communication tool, facilitating planning coordination among the design team, the robotic team, and manufacturers interested in remanufacturing. Moreover, it proves beneficial in the early design phase, when determining fasteners for the product, for instance the irreversible snap-fit. Implementing uniform fastener systems could significantly reduce the frequency of tool changes in an automated disassembly process, thereby enhancing time efficiency. Also selectively disabling high-force fasteners where high-value electronics are located could effectively minimize the risk of damage during the disassembly process. Another approach involves carefully considering the precise location of the target components given the limitations of tools and robotic systems for disassembly. Implementing the action of prying (to move or lift something by pressing a tool against a fixed point) on robotic manipulators can be complex, because it requires feedback to accomplish the separation of parts, e.g. for snapping the PCB from the plastic stems that hold it in place. Corrective feedback would require complex sensorization, i.e., visual, haptic, force-torque.

6. Conclusion

Our initial study demonstrates the feasibility of automatically programming robot solutions based on design data. This process involves extracting a Bill of Material (BoM), Bill of Tools (BoT), and Bill of Process (BoP) from the design data. These three tools are then utilized to create the robotics program with minimal to no operator intervention. For these components to contain the necessary information, however, they must be an integrated part of the design process. The value of creating a disassembly map is that it inherently contains information about subparts of the product (BoM), how the product should be disassembled (BoP), and which tools are needed (BoT). Hence, structuring the design data as part of the product development phase is the key to future remanufacturing.

Simplifying general programming is imperative. Even a seemingly straightforward drilling operation involves multiple robot motions, and any changes in the product's position or the introduction of a similar but slightly different product may necessitate re-teaching all actions.

The ability to overcome uncertainties is also hard to guarantee using traditional robot programming. However, the product's CAD data is a requirement for automatic programming. Therefore, we propose the following approach: Augment the CAD data with additional information describing how a specific disassembly action should be performed. This information can be based on a catalogue of parameterized actions, with parameters tailored to the specific case. This would be ideal to integrate into the design process of the products.

References

Badurdeen, F., Aydin, R. and Brown, A., (2018), "A multiple lifecycle-based approach to sustainable product configuration design", *Journal of cleaner production*, Vol. 200, pp. 756-769. https://doi.org/10.1016/j.jclepro.2018.07.317

Baldé, C.P., Yamamoto, T., and Forti, V. (2023), Datasets on invisible e-waste supporting the International E-waste Day 2023 - Statistical Briefing, United Nations Institute for Training and Research, Bonn, Germany.

Bogue, R. (2007), "Design for disassembly: a critical twenty-first century discipline", *Assembly Automation*, Vol. 27 No. 4, pp. 285-289. https://doi.org/10.1108/01445150710827069

Dario, P., Rucci, M., Guadagnini, C. and Laschi, C. (1994), "An investigation on a robot system for disassembly automation", Proceedings of the 1994 IEEE International Conference on Robotics and Automation, San Diego, CA, USA, pp. (1994), "An investigation on a robot system for disassembly automation", *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*, San Diego, CA, USA, Vol 4, pp. 3515-3521. https://doi.org/10.1109/ROBOT.1994.351030

De Fazio, F., Bakker, C., Flipsen, B. and Balkenende, R. (2021), "The Disassembly Map: A new method to enhance design for product repairability", *Journal of Cleaner Production*, Vol. 320 No. 128552, pp. 1 - 12. https://doi.org/10.1016/j.jclepro.2021.128552

Engelen, B., De Marelle, D., Kellens, K. and Peeters, R.J. (2023), "Intuitive teaching approach for robotic disassembly", *30th CIRP Life Cycle Engineering Conference*, Procedia CIRP, Vol. 116, pp. 384-389. https://doi.org/10.1016/j.procir.2023.02.065

Favi, C. Marconi, M., Germani, M. and Mandolini, M. (2019), "A design for disassembly tool oriented to mechatronic product de-manufacturing and recycling", *Advanced Engineering Informatics*, Vol 39, pp. 62-79. https://doi.org/10.1016/j.aei.2018.11.008

Hochwallner, M., Sundin, E., and Johansen, K. (2022), "Automation in Remanufacturing: Applying Sealant on a Car Component," In: Ng, A.H.C. Ng, Syberfeldt, A., Högberg, D. and Holm, M. (Eds.), *SPS2022: Proceedings of the 10th Swedish Production Symposium* (Advances in Transdisciplinary Engineering 21), IOS Press, Amsterdam, pp. 147–158, https://doi.org/10.3233/ATDE220134

ISO (2015), ISO 14001:2015: Environmental management systems - Requirements with guidance for use, International Organization for Standardization, Geneva.

Lee, H.M., Sundin, E. and Nasr, N. (2012), "Review of end-of-life management issues in sustainable electronic products" In Seliger, G. (Ed.) *Sustainable Manufacturing*. Springer, Berlin, Heidelberg, pp. 119-124. https://doi.org/10.1007/978-3-642-27290-5_18

Lieder, M. & Rashid, A. 2016, "Towards circular economy implementation: a comprehensive review in context of manufacturing industry", *Journal of cleaner production*, Vol. 115, pp. 36-51. https://doi.org/10.1016/j.jclepro.2015.12.042

Lu, Q., Ren, Y., Jin, H., Meng, L., Li, L., Zhang, C. and Sutherland, J.W. (2020), "A hybrid metaheuristic algorithm for a profit-oriented and energy-efficient disassembly sequencing problem", *Robotics and Computer-Integrated Manufacturing*, Vol. 61, pp. 1-10. https://doi.org/10.1016/j.rcim.2019.101828

Mandolini, M., Favi, C., Germani, M. and Marconi, M. (2018), "Time-based disassembly method: how to assess the best disassembly sequence and time of target components in complex products", *Advanced Manufacturing Technology*, Vol. 95, pp. 409-430. https://doi.org/10.1007/s00170-017-1201-5

Marconi, M., Palmieri, G., Callegari, M. and Germani, M. (2019), "Feasibility Study and Design of an Automatic System for Electronic Components Disassembly", *Journal of Manufacturing Science and Engineering*, Vol. 141 No. 2. https://doi.org/10.1115/1.4042006

Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G. et al. (2017), Critical Raw Materials and the Circular Economy – Background report, EUR 28832 EN, Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/378123

Stahel, W.R. (2016), "Circular economy", *Nature*, Vol. 531, No. 7595, pp. 435-438. https://doi.org/10.1038/531435a

Sundin, E., Elo, K. and Mien Lee, H. (2012), "Design for automatic end-of-life processes", *Assembly Automation*, Vol. 32 No. 4, pp. 389-398. https://doi.org/10.1108/01445151211262447