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Concepts and Requirements for Flexible Disassembly Systems for Drive Train Components of Electric Vehicles

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Abstract

An increase in the sales number of battery electric vehicles within the last year can be recorded. At the end-of-life these vehicles require a reliable disassembly for recycling or remanufacturing. On the one hand, drivetrain components of those vehicles contain valuable resources and thus are mainly relevant for recycling or remanufacturing. On the other hand, the automated disassembly of especially electric motors and Li-ion battery systems encloses major challenges. Especially the high number of variants and the unknown specifications and conditions of the components are challenging points for the disassembly system. Conventional automated disassembly systems provide limited flexibility and adaptability for the disassembly of these products. Within this contribution two robot-based flexible disassembly systems are systematically derived for Li-ion battery modules and supplementary electric motors.

Both products are analysed and the product-specific challenges and requirements are identified. The state of the art regarding flexible disassembly systems is captured using the methodology of a morphological box. Four subsystems are identified: Kinematic, Tools, Workpiece fixation, Safety system. Based on the results, concepts for disassembly systems for both Li-ion battery modules and supplementary electric motors are developed and presented in detail. Especially the structure and functionality of both systems are explained. This is followed by an assessment of the approaches and an identification of limitations as well as possible optimization potentials.

Keywords: Agile Disassembly System; Disassembly; Robot

1. Introduction

Battery Electric Vehicles (BEV) have gained importance and are becoming evermore present, which can be seen in the worldwide increase in sales volumes in recent years [1]. The large quantity of vehicles consequently leads to an increased after market and the question for after-life treatment emerges. With the rising ecological consciousness of consumers and businesses, the available after-life treatment strategies are challenged for sustainability. Possible strategies for a sustainable treatment of end-of-life products are reuse, remanufacturing or recycling [2, 3]. For recycling strategies, the extraction of valuable resources from traction batteries and motors requires a reliable dismantling process. It is economically beneficial to regain substances like lithium, cobalt or nickel [4] which also leads to an increased independency from imported raw materials. Therefore, an industrial process is required of which disassembly to a granular structure takes in a key role. Asides, remanufacturing has proven as an effective way for resource efficient manufacturing [5]. During this process, there are valuable components extracted from the assembly and fed back into the production cycle. Remanufacturing requires the disassembly of assemblies to smaller sub-assemblies. Du et. al [6] highlights the importance of the disassembly process step within the general remanufacturing pipeline for being the key link that connects product return with product recovery. On the one hand, remanufacturing can possibly save a high amount of resources, but on the other hand, there are several major challenges to deal with for a robust realization in large scale applications. Because of the numerous advantages of both presented after-life treatment strategies, an increased number of disassembly tasks is assumed in future which therefore requires automated solutions. By automating a task, several advantages arise. Complex technological processes can be realized with a constant quality, whereby harms for human workers can be minimized at the same time. A constant operation of the plant is viable and a fast

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and inexpensive adaption of the production is feasible [7]. However, the automated disassembly of components is accompanied by many challenges. One of the main challenges is implied in the design of the product. A higher-level assessment reveals two different kinds of product categories with the difference lying in the ease of product disassembly. The first category is represented by complex products with a poor disassemblability [8] which are characterized by a high number of connections and product variants. The second category consists of standardized and less complex products having good disassemblability and minor number of connections. The latter mentioned category of products can be disassembled by automated transfer lines. The focus of this contribution lies on flexible automated disassembly systems which is addressing the first mentioned product category. The exposure of the products to different environments results in physical changes during their lifecycles and thus leads to product uncertainties which represents another challenge for automated disassembly systems. Besides the described product-related challenges, there are organizational issues such as the availability of goods on the market [9]. Furthermore, there are safety restraints to be dealt with, especially when it comes to BEV.

The research objective within this contribution is to systematically derive two automated flexile disassembly systems for both Li-ion battery modules as well as supplementary electric motors based on the analysis of the products and state of the art solutions.

2. Methodology

Initially, the products Li-ion battery modules and supplementary electric motors are examined and specific challenges as well as requirements are highlighted. Afterwards, state of the art solutions of flexible disassembly systems are investigated. Based on the analysis of the state of the art, a morphological box of flexible automated disassembly system is derived. The morphological box serves as a blueprint and allows the generation of two exemplary flexible disassembly systems for the regarded products. The essential subsystems of those systems are introduced and discussed in detail. Finally, the presented approaches are assessed and the limits as well as the possible optimization potentials are identified.

3. Product analysis

In the following, the required basics regarding Li-ion batteries and the observed electric motors are introduced. Furthermore, the specific challenges and requirement for disassembly are identified.

Li-ion batteries can be divided into three hierarchical levels: battery system, battery module and battery cell. In particular, the cells contain valuable materials such as lithium, nickel, cobalt, aluminum and copper, which were also the focus of the LithoRec recycling project. [4] Current research has already investigated the disassembly of battery systems, such as the disassembly of Audi Q5 traction batteries into modules

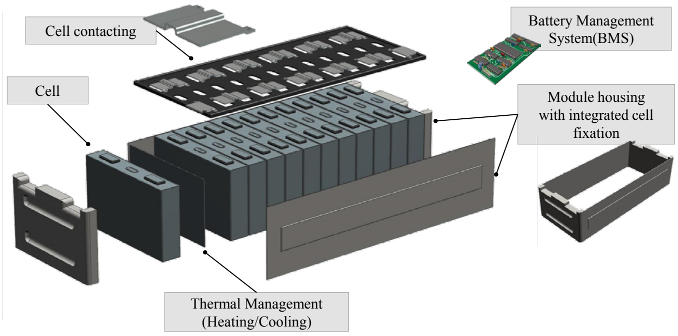

Fig. 1. Example setup of a battery module with prismatic cells

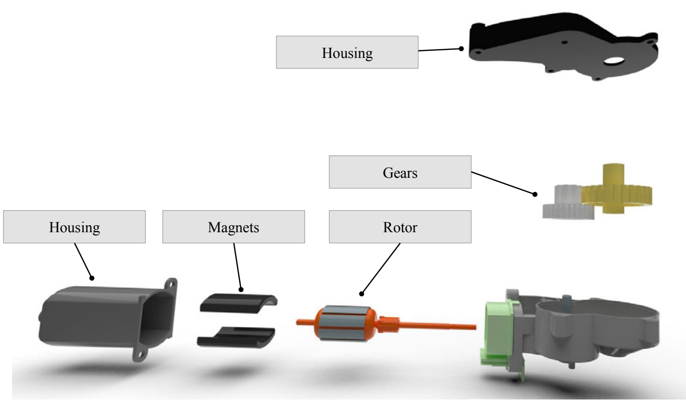

Fig. 2. Example supplementary electric motor

[10]. This paper focuses on the dismantling from battery module to cell due to the lack of research activities. An example setup of a battery module with prismatic cells which shows the basic components according to [11] is illustrated in Fig. 1. The module consists essentially of the components: cell, cell contacting, thermal management, module housing, cell fixation and battery management system (BMS). Disassembly of systems into subsystems can potentially increase the purity of the fraction and enables the extraction of functional components for remanufacturing purposes [2]. However, the disassembly of battery module to cells is accompanied by different challenges. On the one hand, the high variety of the battery modules is a product-related challenge. On the other hand, the battery cells pose a wide range of hazards, which in combination with the need of destructive separation methods due to non-detachable joints represents a process-related challenge [11]. Furthermore, an irreversible volume change due to chemical reactions can be observed over the lifetime of the cells [12], which manifests itself as a geometrical uncertainty at the battery module level and can therefore be seen as another major challenge. The scope of the disassembly is the extraction of the battery cells, which can be used for further recycling steps or 2-end life applications. Since there is currently a high number of variants with different manifestations of the components [11], no general dismantling

sequence can be defined. Instead, certain core process steps can be identified which are presented at the end of the chapter.

Electric motors represent another important partial system of the electric drive train. At the end of life of electrical motors nowadays mainly copper and aluminum is regained by destructive disassembly. Within this contribution particularly permanent-magnet synchronous motors as shown in Fig. 2 are regarded. The motor housing is opened and rotor and stator are separated. The rotor is disassembled and copper windings are retracted using hydraulic tools. A subsequent processing of permanent-magnets is required as well. Alternatively to the material recycling, the motors can be remanufactured. Therefore, the housing is opened in a partly-destructive or non-destructive manner and the valuable rotor is extracted. The separated parts are refurbished if required and fed back into the assembly process. Special requirement within the dismantling for remanufacturing is the loss of the mechanical integrity of the structure. Depending on the motor type, forces emerging from the permanent magnets have to be compensated. The disassembly system needs to adapt to varying product conditions. Additionally, the exposed environments during the life phase lead to an unknown state of the part upon arrival at the disassembly system.

Based on the analysis of both products and under consideration of VDI 2860 [13] and VDI 8580 [14] common core process steps which should be fulfilled by the disassembly system are identified and are listed in the following:

- Handling of product and components
- Clamping of product
- Separation of connections
- Checking of product and component state

4. State of the art

The current state of the art of disassembly systems is summarized in the following.

Flexible automated disassembly has received a lot of attention from academia within recent years. A diverse range of products are at the focus of the automated dismantling process. The first example is the work at the Technical University of Berlin, which deals with the robot-assisted disassembly of washing machines [15], LCD displays [16] and mobile phones [17]. In the first mentioned work several 6-axis robots are used, the latter both utilize a SCARA robot as kinematic. A further contribution in the field of automated disassembly was carried out at the Vienna University of Technology with the disassembly line for mobile phones with various specialized stations [18] as well as a robot-assisted disassembly system for printed circuit boards [19]. Worth mentioning in this context is the project at the University of Alicante, where two collaborating 6-axis robots are used to disassemble PC into its components [20]. A relevant disassembly project in the context of electric mobility was conducted at Technical University of Braunschweig with the robot-assisted dismantling of Li-ion traction batteries of an Audi Q5. One of the research topics of the mentioned work was the loosening of screw connections in the human-robot environment [10].

The tools used for the disassembly can be divided in principle according to the operation classes: handling [13] and separation tools [14]. The handling tools are for example suction or finger grippers as used in the work of [16, 17, 18, 19, 20]. According to VDI 2343 [21], separation tools can be distinguished into non-destructive tools such as screwdrivers [15, 16, 17, 20, 10] or destructive ones such as drilling spindles [19] or plasma cutters [15]. VDI 2343 introduces a more granular distinction between semi-destructive and destructive dismantling, within this publication it is summarized as destructive separation. Depending on the present joint either destructive or non-destructive separation method can be used. Destructive separation is characterized by the destruction at least one connecting component or generating a new separation point by irreversibly damaging a component in order to enable the separation of a joint [21].

A common feature of all listed operations dealing with the disassembly of different products is the use of at least one 6-axis robot or SCARA robot. The choice of this type of kinematics is well justified by the high flexibility with sufficient stiffness and load capacity. The process flexibility is realized either on tool level e.g. by using multifunctional tools like multipurpose grippers [19] or by exchanging the tool by an interchangeable system [20]. The flexibility towards product variety can be realized especially on the software level, for example by conducting an automated disassembly sequence and process planning for each product [15]. Based on an emulation process, a control code for the disassembly of a product can be generated and loaded onto the PLC.

In conclusion, a wide variety of academic research works in the field of flexible automated disassembly with different kinds of disassembly objects can be identified. Thereby the requirements for disassembly are fulfilled by different kinds of tools and further subsystems. The hardware flexibility of the disassembly system is especially realized on the kinematic as well as on the tool level. On the kinematic level, the utilization of at least one 6-axis robot reveals maximum freedom of movement. On the tool level, the flexibility is achieved by flexible end effectors or end effector changes.

In the following, an approach for capturing the manifestations of the subsystems of state of the art disassembly systems by using the methodology of morphological box is presented.

5. Blueprint for flexible disassembly system

The state of the art exposes subsystems with various manifestations which fulfil the requirements for flexible disassembly in different ways. A morphological box is used as an approach for capturing the different kinds of subsystems of the presented disassembly systems from previous chapter. Fig. 3 illustrates an extract of the morphological box. Additionally, other manifestations which can be found in assembly systems are added to the morphological box. In principle, a distinction can be made between the following subsystems: *Kinematic*, *Tools*, *Workpiece*

Subsystems		Manifistation								
Kinematic	Kinematic chain	Open			Closed			Partly closed		
	Implementation	1. Vertical articulated robot	2. SCARA	3. Gantry	1. Delta kinematics	2. Tripod	3. Hexapod	1. Tricept		
Tools	Type	Gripper		Machining tool						Measuring tool
	Process	Handling		Separation						Measuring
	Implementation	1. Mechanical Gripper	2. Pneumatic (vacuum) Gripper	1. Screw driver	2. Drilling/ milling spindle	3. Angle grinder	4. Pulling tool	5. Shear cutting	6. Snap fit disassembly device	1. Measuring tip
		3. (Electro-) magnetic gripper	4. Material closure	7. Plasma cutting	8. Laser cutting	9. Water jet cutting	10. Oxy-fuel cutting	11. Heating systems		2. Visual system
Workpiece Fixation	Working principle	Force fit		Force/form fit						
	Implementation	1. Suction clamp	2. Magnetic clamp	1. Pneumatic clamp	2. Electric clamp	3. Manual clamp				
Safety system	Type	Passive		Active						
	Implementation	1. Safety fence	2. Warning labels	1. Sensorical supervision	2. 2-hand-steering	3. Emergency switch				

Fig. 3. Extract of morphological box of flexible automated disassembly system

fixation, *Safety system*. The *Kinematic* is responsible for the movement of the workpiece or work tool. *Kinematic* can be distinguished according to their kinematic chain: open, closed, partly closed [22]. The actual process takes place between the *Tools* and the workpiece. The *Tools* can be basically divided into gripper, processing tool and measuring tool. The *Workpiece Fixation* can be seen as additional periphery and has the function of fixing the workpiece during the machining process, either by force or force/form-fit [23]. The *Safety system* provides protection for external persons. This can be done passively, for example by a safety fence, and/or actively by emergency switches [22]. Other possible subsystems to be mentioned are the transport system and the control system. The presented morphological box serves as a blueprint for generating flexible automated disassembly systems.

6. Derivation of flexible disassembly systems

Within this chapter, two different disassembly systems based on the morphological box are introduced and described. Both solutions are part of research projects addressing the flexibility of (re)manufacturing systems.

6.1. Disassembly system for battery modules

The first example represents a concept for a flexible automated disassembly system for Li-ion battery modules. A corresponding depiction of the disassembly system is shown in Fig. 4. Mandatory operations for disassembly of Li-ion battery modules as described in chapter 3 are handling, separation, clamping and monitoring operations. Handling and separation (especially cutting) operations place demand on the kinematic in terms of accuracy, rigidity and load capacity. These mentioned operations are fulfilled by tools at each robot. In the presented concept two operation-specialized 6-axis robots are utilized as kinematics. While one robot is responsible for handling operations, the other robot is used for separation operations. If required, an automated tool change can take place, corresponding for this are modular designed tools, tool magazines as well as tool self-clamping device at each robot. It is recommended to reduce the tool change to a minimum, as each tool change is associated with equipment downtime. To reduce tool changes it is recommended that the handling and cutting tools cover a large operation parameter space and offer a high level of compatibility with various materials and geometry. For example, a gripper should cover a wide stroke range while a separating tool like a drill is requested to deal with different types of joints. If the tool reaches its limits, an automatic tool change is necessary. A clamping device which is flexible to any kind of contours enables fixing the different-sized modules in various positions. The transportation of the battery modules in the disassembly system and the extracted components out of the system can be fulfilled by a belt conveyer. A transverse conveyor belt serves as a support surface for magazines storing the extracted components. In addition to the mentioned requirements for disassembly system, the mentioned hazards posed by Li-ion batteries requires a special treatment as well as a continuous monitoring of the battery state. Thus, the disassembly system is designed as a hermetically lockable disassembly cell. In an emergency case, the system seals off from the outside world by closing the entrance and exit gates. Status monitoring can for example be done by using thermal camera continuously detecting the current temperature of the Li-ion cells. In addition, 3D scanning devices offer the possibility to scan the topography of the battery module in order to capture geometrical uncertainties. The presented disassembly system for battery modules has not yet been finally realized und thus should be regarded as a concept.

6.2. Disassembly system for supplementary electric motors

In order to meet the previously described requirements of the disassembly of an electric motor, appropriate elements are selected from the morphological box. The automated disassembly system is depicted in Fig. 5. For the kinematic subsystem two vertically articulated industrial robots are selected and arranged on a joint working table. The robots are equipped with different tools and additional periphery for the system is included. A mechanical gripper is utilized as well as a special disassembly end effector. The workpiece fixation is achieved by a flexible clamping system. The clamping system can adapt to the geometrical shape of the products to be disassembled. The end effector is a screw driving tool, which can regulate the process forces and torques. Additionally, the station is equipped with two depth-cameras, which allow the generation of point clouds.

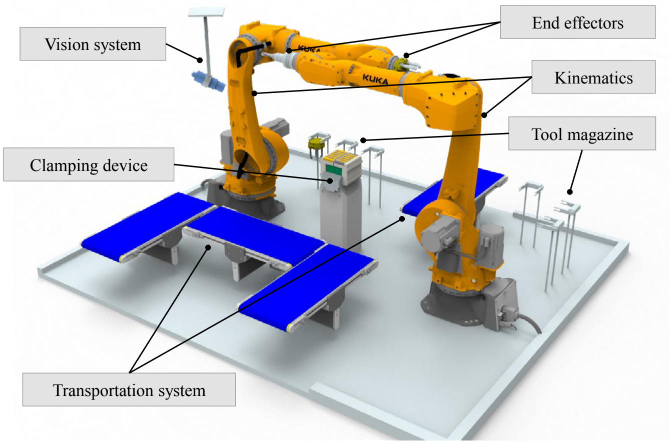

Fig. 4. Concept for a disassembly system for Li-ion modules consisting of two operation-specialized robots

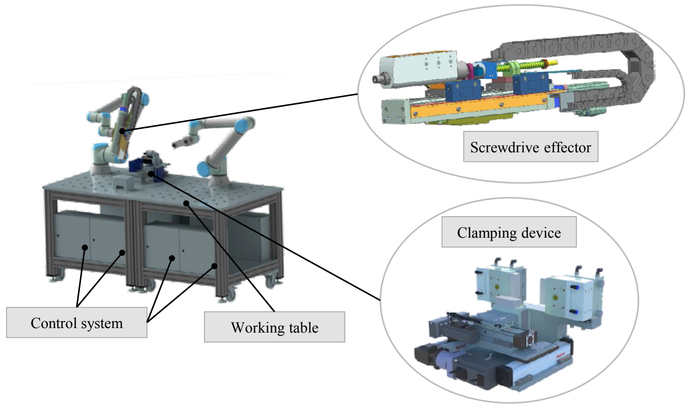

Fig. 5. Disassembly system for electric motors

These are used for the generation of the movement commands of the robots. One of the cameras is held in the robot arm and the other one focusses on the working area. The point clouds are being segmented for the areas and components of interest. The disassembly process steps within this use-case consist of the following steps: (i) product positioning, (ii) product fixation, (iii) removal of screws, (iv) removal of the gear box, (v) removal of gears. In case of disturbances, there are human workers which can support the disassembly line in the process. The disassembly system is part of a disassembly line which consists of four different stations. Additionally, the material flow and transportation of the goods is being realized by mobile robots, which deliver the products and take care of the handling of additional periphery such as product carriers and boxes. After storage and sorting, the products are being inspected at the first station by the utilization of different sensor equipment. The motor defects are being classified and the overall condition is detected. If the motor model type is new to the remanufacturing line, it is directed to a disassembly station, at which a human worker disassembles the motor and the manufacturing system learns from the human behavior. Thereby, additional information on the product is being extracted such as the disassembly precedence graph and special points of interest in the gaze of the human worker. If the motor type is known to the system, the motor is directed to an automated disassembly system, which is able to disassemble the motor components for most of the cases. Afterwards, the sub-assembly groups are directed to a press station where remaining parts are being pushed out by a press system. Finally, all parts are being collected by the mobile robot and are stored at dedicated places.

7. Discussion

A common limit of consideration among both presented systems is the overall view of the agile production system. Consideration must be given to further systems that belong to an agile system, such as overall control system. Additionally, one must face the question whether the process should be workpiece- or tool-guided. While the shown concepts demonstrate a tool-guided approach, the tools are guided by the kinematics, the other approach could be advantageous in some aspects. Hence, a comparison of both approaches on technological and economical level would be useful. Another inevitable point is an economical view on the disassembly system with regard on the required process as well as the extracted materials and functioning components. As long as the economic benefits do not become apparent, this topic remains a matter for research. Furthermore, a closer view to the control system which represents another essential subsystem of the flexible disassembly system is missing. The control system, like the other subsystems, are requested to be flexible regarding product variety and robust against product uncertainties.

8. Conclusion and outlook

Within this paper two flexible disassembly system prototypes for both Li-ion battery modules and supplementary electric motors are systematically derived based on a product analysis and a flexible disassembly system blueprint. Firstly, an analysis of both products as well as the product-specific challenges and requirements is conducted. Additionally, an examination of the state of the art of flexible disassembly systems is carried out. The methodology of morphological box is used to capture the manifestations of the subsystems. The four identified subsystems are: *Kinematic*, *Tools*, *Workpiece fixation*, *Safety system*. The morphological box serves as a blueprint for generating of both presented disassembly systems. Finally, a discussion of the presented approaches is conducted and the limitations as well as possible optimization potentials are summarized.

As a future object of research, the economical evaluation of the disassembly system needs to be shown. A comparison of the used resources and the obtained materials and components would be appropriate here. Furthermore, a consideration of the entire production system, considering other disciplines such as logistics or warehousing, would be very beneficial. The overall vision of the presented research projects is an agile disassembly plant processing different kind of products. The same system handle both the disassembly of Li-ion traction batteries as well as the disassembly of electric motors.

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