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Investigation of the potential for an automated disassembly process of BEV batteries

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Abstract

Current electric vehicle battery recycling processes often begin with the manual dismantling of the battery packs. In consideration of occupational safety and in view of the increasing sales of electric vehicles, an automated dismantling of batteries has to be investigated. Therefore, different manufacturers' battery pack designs are examined first and especially the common joining elements are determined and characterized. The results show a high diversity between the individual systems, which influences the potential for automation. Based on these investigations, a possible layout of an automated dismantling cell is developed.

Keywords: Disassembly; Recycling; Automation; Electric vehicle; Battery

1. Introduction

Many people see the fight against climate change as an urgent goal in today's world. Decisive factors in this fight are the reduction of emissions of greenhouse gases. In this context, carbon dioxide emission (CO2) is repeatedly cited as a driver greenhouse effect driver. With a share of 20%, the current transport sector makes a not inconsiderable contribution to all CO2-emissions of the European Union (EU). Cars and vans are responsible for 70% of those emissions [1]. Therefore, manufacturers of mobility technologies are trying to bring increasingly efficient systems to the market.

National governments and the EU are trying to encourage manufacturers to develop and build more fuel-efficient cars with low emissions using appropriate guidelines. For example, limit values for the CO2 emissions of a manufacturer's fleet have been agreed upon since 2020. One way to achieve the targets and reduce emissions is to use hybrid or electric vehicles (EV), as they do not produce emissions at the "tailpipe".

Current figures show that sales of EVs have risen exponentially in recent years (see Fig. 1). Forecasts show that these rates may increase even more in the future. Due to the rising sales of electric vehicles, more and more lithium-ion batteries (LIB), which are mainly used in electric mobility, are required, produced and used in EVs. After the use, at the end of life, there can be different ways for the batteries. Some battery systems can be reused without significant changes, for example, in energy storage systems. During remanufacturing, non-functional components can be replaced to return the product to a like-new condition. In the context of recycling, the recovery of materials is focused. This is even more important since the mining of the materials required for the batteries' production is often carried out under cost-intensive and environmentally harmful conditions.

The non-functional components or parts with the same materials must be dismantled to prepare the batteries for remanufacturing or recycling. As increasing numbers of unusable battery systems are expected (see Fig. 1), a flexible

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and automated disassembly system is necessary to initiate an environmentally friendly and cost-effective recycling process.

This article presents an approach to estimate the potential for an automated dismantling process required to initiate the subsequent recycling process as efficiently as possible. The focus is on currently sold battery systems. In the study, the dismantling of the packs to module-level (pack2module) was analyzed.

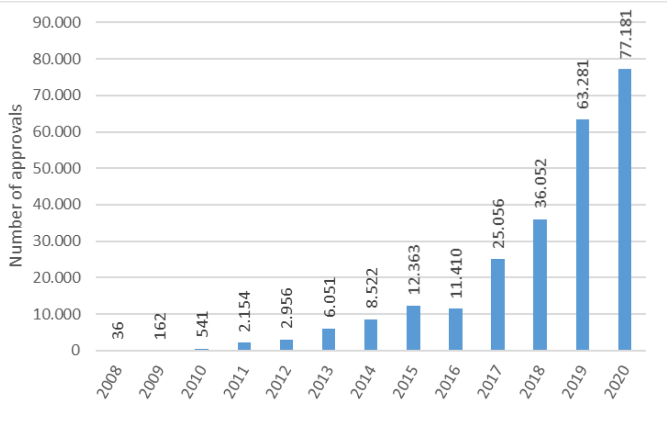

Fig. 1. Approvals of electric-powered vehicles in Germany from 2008 till August 2020 (derived from [2])

In the following, the existing recycling processes of batteries for electromobility will be discussed first. Then, current battery pack designs are analyzed, and the necessary dismantling steps are derived. At the same time, the potential for automated execution of the steps is estimated. Finally, a possible division of the steps is worked out and the challenges involved are pointed out.

2. State of the Art

Disposal or recycling represents the last phase in the typical product life cycle, with several reasons for recycling the products [3]. When recycling a product, the primary motivation is to prepare contained components or materials for reuse, thus saving and conserving natural [4]. Secondary reasons for the recycling of products are environmental protection through less emissions. In addition, costs can be saved in scrapping, as no storage space is required for scrapped components [4]. Especially concerning LIB, these goals are very much in the foreground due to limited resources. The recycling of the required lithium-ion batteries is regulated in the European Union by 2000/53/EC and 2006/66/EC.

Current developments in recycling of batteries are mainly working on the recovery and separation of the individual cell components. This fact is comprehensible since the cost-intensive components are mainly located in the cell. For an efficient recycling process, however, it may be essential to separate the materials of the remaining components in advance [5].

To separate the cell materials, several approaches have been developed. The hydrometallurgical, pyrometallurgical, and mechanical processes have become established as primary methods for recycling LIB cells [6, 7]. Hydrometallurgical and pyrometallurgical processes are used to separate cell components, whereas mechanical processes are often used as a pre-treatment stage and are used for crushing battery cells. Individual materials such as metals and plastic parts can be separated, e.g., by shaking or sieving [6, 8, 9]. Besides, there are approaches for so-called direct recycling, whereby individual components of the LIB are processed and directly reused [8]. Also, individual electrode materials will be regenerated, for example, with supercritical carbon dioxide [6, 10]. Furthermore, processes are applied, which often represent combinations of basic recycling methods. An example is the Duesenfeld process [11].

The dismantling of a LIB before the actual recycling process contributes significantly to optimizing the entire recycling process regarding environmental friendliness [12]. The degree of automation of LIB's dismantling is currently low due to many variants and the rarely accessible design data [13]. Hermann et al. already introduced an assessment approach to identify the automation potential of traction batteries' disassembly [14]. In the article, they define a criteria catalog to determine the potential.

There are currently several partially automated approaches for the dismantling of LIB. Wegener et al. present a hybrid human-robot dismantling station, where a robot arm performs repetitive tasks such as loosening screws. One difficulty is recognizing and handling the robot arm with the screw heads, for which the authors show some possible solutions [13]. Schäfer et al. developed an automated remanufacturing station for individual battery modules based on an analysis of the joining techniques used. Welded connections between the cells are separated using a milling unit [15]. Hermann et al. present a concept for a hybrid dismantling station. They suggest removal of electronics' manually and the removal of modules with an articulated arm as a robot unit and jaw grippers. The concept should be extendable to a fully automated disassembly station [16]. Barwood et al. designed a fully automated dismantling cell consisting of a Stäubli robot, a modular mounting platform, and specially designed tools [17]. Bloemeke et al. showed an overall approach for an advanced circular economy on the example of EV recycling. In addition, they present a concept of a robot cognition disassembly system to meet the challenges of product variety [18].

It becomes clear that many approaches to automating dismantling are currently under development. The current state of the art is preferably in partially automated concepts since full automation is associated with various difficulties. To overcome these challenges, this article investigates the battery packs' design to support companies when planning, building and operating automated disassembly cells. The determined data provide values that are required in the criteria list of Herrmann et al. [14].

3. Potential Determination for an Automated Disassembly of Traction Batteries

In the assembly of goods, precisely defined components are connected and assembled to form a product. Original Equipment Manufacturers have precise knowledge about the status of the corresponding components. On the other hand, there is disassembly, where the product's use may have resulted in changes to the original condition. Also, the disassembly of products does not necessarily have to be carried out by the manufacturer. Thus, it happens that recovery companies take over the dismantling and recycling of the used products to make valuable materials usable again for the production of new systems. Consequently, the necessary processes must be developed since only the manufacturer knows the precise structure of the products. An automatic approach to dismantling could lead to an increased recycling rate and lower costs for the materials required in production. To analyze the dismantling of packs to the module level, we will first attempt to describe the structure of the product "battery" as generally as possible. The required processes are derived from this afterwards in section 3.2.

3.1. Analysis of Battery design

In the first step, battery assemblies of different models were analyzed to derive possible strategies for dismantling. The investigated models are chosen because of their high sales volume or the publicly available product information. Mostly, videos showing dismantling had to be used for the evaluation, as manufacturers often do not publish details. These videos were mainly taken by amateur filmmakers, so that not all primary conditions are known. However, care was taken during the evaluation to ensure that only correspondingly clear information was used for evaluations. Also, scientific references and information from car manufacturers were used to gain further information. The cars examined included Chevrolet Bolt [19, 20], Nissan Leaf [21, 22], VW eUp [23], BMWi3 [24, 25], and Tesla Model 3 [26-28].

In the beginning, components were combined into suitable assemblies, which can be dismantled in one process step and, if necessary, even recycled as one unit. Here, both the connections and the materials were considered. The classification for the subassemblies is derived from [29] and represents a corresponding class. With this classification, movement and gripping processes can be classified and subsequently evaluated.

The flat components include, for example, the cover of the battery pack and cover plates inside the pack. Prismatic parts have a basic rectangular-shaped structure. Typical non-rigid parts are, for example, wires and cables as they deform under gravity during handling. Another class represents cylindrical components which do not occur in the investigated batteries. Components for connection, e.g. screws, are not considered in this first step since these are taken into account in the investigation of the connection types. However, the disassembly system needs also to be equipped in order to deal with these components.

The investigations show that mainly flat and prismatic components are built into the packs (see Fig. 2). Unfortunately, however, the remaining 12% consist of non-rigid components often lead to increased dismantling costs or make automation uneconomic. Table 1 lists the component classes of the battery according to their automated handleability [29]. Within the table, the handleability decreases to the right and below. One example is the handling of modules. These prismatic components have characteristics at the edges and surfaces so that handling is only possible at specific points. If additional cables are permanently connected, automation can be even more difficult as the handling is further limited.

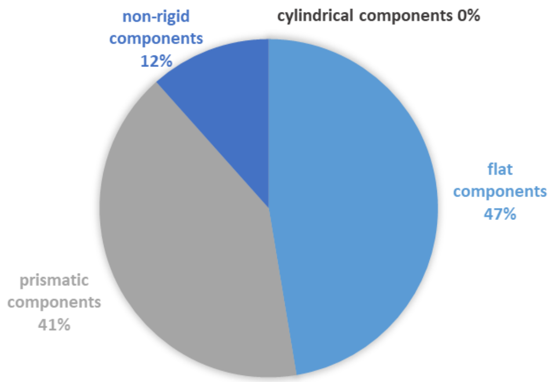

Fig 2. Distribution of the general components in a battery pack

Comparing the information from Fig. 1 with the data from Table 1, it becomes clear that about 12% of the components make handling automation considerably more difficult. In the future, it should be considered whether appropriate gripping strategies can be developed to make handling easier. Depending on how recycling is implemented, processes can be examined, which may destroy the surface or shape. This could lead to a decreased effort for automation.

Table 1. Classification of handling parts in a battery pack (derived from [28]).

shape	flat	prismatic	non-rigid
Part with even surface	Battery cover	Connecting bars in the pack (BUS-Bars)	Cables
Part with characteristics in inner and outer shape	Cover sheets with holes	Battery modules	Cable with irregular insulation
Part with excentric elements	Curved cover sheets	Battery modules with connection cable	Cable harness
Irregular composed parts	-	Assembled electronic components	Cable with connected components

Another decisive factor in dismantling is the type of connection between the individual components. These connections must be separated during dismantling. A decisive factor is the non-destructive or destructive separation of the materials. Some connections are built to be separated again destructively (e.g., welding). On the other hand, there are connections such as screws, which can be more easily separated with the appropriate tools. As can be seen in Fig. 3, mainly screw connections are used in battery design.

During the evaluation, it was noticeable that there is a wide range of simultaneously used connection types in a battery pack. However, only in one case, all listed connection types were present in the package. Most of the packs use between two and four different connection types.

These aspects should be taken into account when planning (dis)assembly systems. Therefore, priority should be given to processes that can solve these connections efficiently. However, since these are average values, it must be checked whether the whole disassembly system can handle the corresponding battery pack.

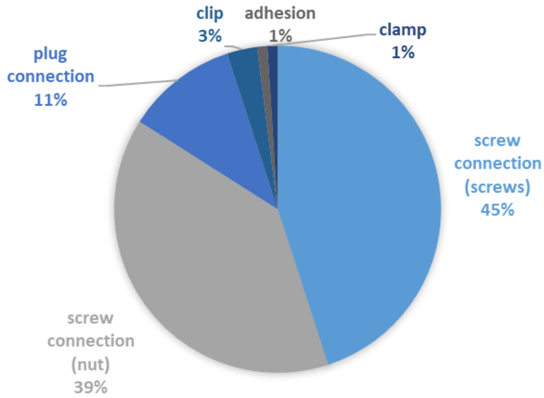

Fig. 3. Distribution of the different type of connections in a battery pack

3.2. Process Steps

One goal of this article is to generalize these steps so that the systems' planning can be carried out more quickly. The dismantling itself can be considered as a separation of the components. DIN 8591 categorizes different processes steps of dismantling, which are used for the further general description.

- Disassemble,
- Empty,
- Loosen frictional connections,
- Disassembly of parts joined by original shapes,
- Desoldering,
- Loosening of adhesive joints,
- Disassembling of textile connections

Considering this list and the developed knowledge about components and connections, almost all mentioned process steps occur during the disassembly of LIBs. Exceptions are the processes "Disassemble" and "Diassemling of textile connections", which are not required when disassembling LIBs. Disassemble describes the separation of components that adhere to each other only by gravity.

The other listed processes take place during the disassembly of such batteries. Emptying takes place, for example, when draining coolant. The disassembly of riveted connections is covered by the term "disassembly of parts joined by original forms". Many electrical components are usually soldered in the battery. This paper will mainly focus on the disassembly of frictional connections, disassembly of parts joined by original shapes, desoldering, and removal of adhesive connections.

Based on the initial product analysis and the previous research, a general classification of the LIB disassembly into the four phases “preparation, disassemble, handling, and store” was made (see Fig. 4). It is assumed that the battery has already been freed from the coolant and is in a discharged state. The preparation starts with the battery's feeding to the disassembly cell and the transport to the final processing position. In this processing position, the battery is fixed for subsequent disassembly. Also, the condition of the battery must be assessed concerning deformation and damage. The disassembly starts with identifying a component to be disassembled or the connections to be loosened and a corresponding selection of tools. The disassembly phase ends with the loosening of the present connection. The subsequent handling phase includes the gripping of the detached component, its removal from the battery system, and its deposit for further transport. During the final storage phase, the loosened and deposited individual part is transported out of the disassembly cell to a storage facility. The individual parts can be fed into a subsequent recycling process according to their specifications. The last three phases of disassembling, handling, and store form a repeating loop for each component until the battery is entirely dismantled.

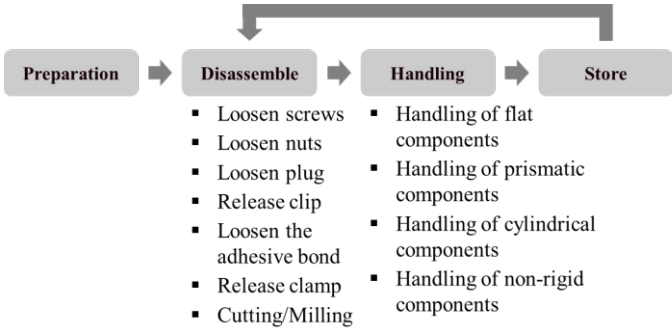

Fig. 4. Illustration of the process sequence and steps in disassembly and handling

The disassembly process is divided into seven subfunctions with respect to the determined connections (see Fig. 4). These separation tasks are derived from the investigations of connection types and have to be addressed in the automation cell. Cutting and milling were added to give an opportunity when the connection is solidified or inseparable (e.g., the bonding of the cells). In this case, the connection or at least one of the joining partners can be destroyed to continue with the dismantling. The handling includes four different classes of components. These parts have to be handled by the robot cell. Of course, they differ, e. g., in size and weight, so that further investigation of the detailed shape must be done. The corresponding distributions indicate about a possible focus in research and the key processes when setting up an automated dismantling cell (see Fig. 2 and 3).

3.3. Uncertainties and Safety

A decisive factor in the successful dismantling of products is the consideration of uncertainties, as these cannot always be predicted. Nevertheless, these must be estimated best in advance so that an automation system is adjusted to the situation and can react accordingly.

Uncertainties regarding the status of the battery can arise due to the battery's service life. For example, damage can be caused by crash situations, making successful disassembly difficult or even impossible. At the same time, a damaged cell can, of course, also lead to the safety of the system or the environment being endangered.

When handling LIB, there are general safety risks such as fire, toxic gas formation, or electric shock due to a battery's residual charge [30]. The ohmic discharge of the battery can easily prevent the latter. Also, the other safety risks do not pose a danger to humans in case of a fully automated disassembly. For the automated dismantling, however, other difficulties arise. The removal of components sometimes requires powerful movements of the robot unit [31]. Furthermore, possibly damaged or flexible elements such as cables or plugged connections are difficult to handle [32, 33]. With the disassembly object, unfavorable conditions of fixing elements such as rounded, loose, or rusted screw heads may occur. Some connections, such as weld seams, can vary in their shape so that this poses a challenge for the equipment technology.

Regarding safety issues, battery cells can also be damaged during disassembly, and electrolyte may leak out. When LIB cells are opened, lithium ions' tendency to react exothermically with air or water is a hazard [30]. Consequently, an opening should only be made under safe environmental conditions such as inert gases since damaged cells can lead to dangerous situations.

An automated dismantling cell requires to react to such uncertainties since manual interventions could be dangerous or even impossible under such conditions. These circumstances require a flexible and adjustable design of an automated system.

4. Design Concept for an Automated Disassembly System

With regard to the data collected in section 3, the following general ideas for layouts were developed. As seen in the investigations, the general processes are quite similar in handling and separation over different types of battery packs. However, they differ enormously depending on the manufacturer. Considering the increasing number of batteries, it might be practical for recycling companies to build a flexible cell with a tool changing system to choose the appropriate tools for the respective process step. As the number of batteries increases, specialized cells can be developed since faster process times are required. Although this aspect was not investigated in this article, it can already be essential to consider the three general structures (pouch, prismatic, and cylindrical) to dismantle the modules to cells. This results in significant differences that lead to an increased number of tools in the cell. A detailed examination of the modules like for the packs will be carried out in further research.

A decisive factor in the planning and execution is also safety. For example, safety during dismantling can be increased by carrying out the process in a protective atmosphere. Since the danger derives mainly from the cells, this area should be specially protected. A protective atmosphere, e.g., with inert gas, should then be used when removing the cells from the modules.

The design shown in Fig. 5 allows compliance with the mentioned requirements. The two-stage process of "pack2module" and "module2cell" is also highly scalable in terms of flexibility since new system segments can be directly adapted to the corresponding requirements according to the design. The enclosure guarantees safety while operating costs are reduced by omitting the "pack2module" enclosure.

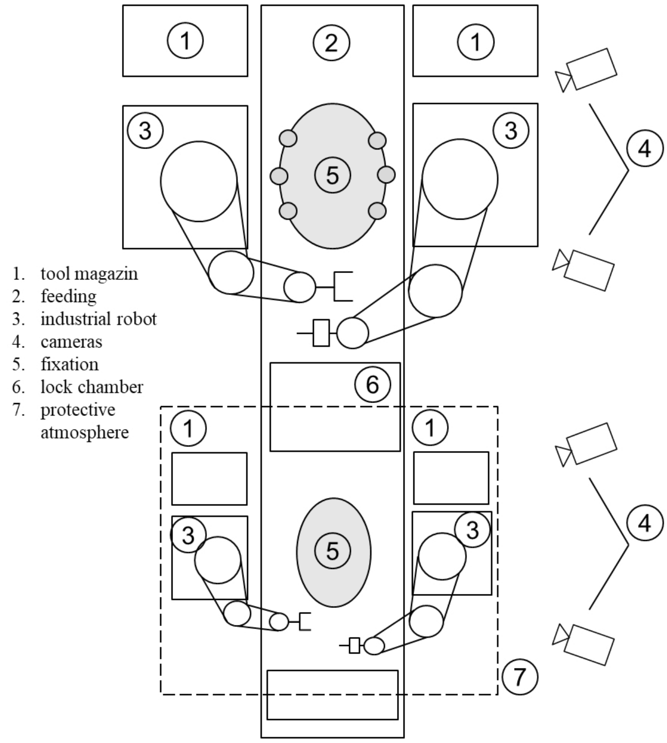

Fig. 5. Concept for a disassembly system

In this layout, there are currently two robots with one tool magazine each. This way, for example, one robot can loosen the connection while the other removes the separated parts. For cost reasons, one robot can also be used, which will probably have a negative effect on cycle times. Flexibility regarding the number of pieces can be achieved by purchasing specific stations of the stage that currently form the bottleneck in the disassembly process. Simultaneously, with a very homogeneous product portfolio, specific stations can be optimized for a particular design. For example, batteries with the same connection types can be processed in the same system. Thus, not all tools have to be kept available at each station. The cameras can be used to monitor the process and to detect uncertainties. These can be solved by the system itself (a cyber-physical system could be useful, as considered in [18]), or a manual operator could arrange appropriate steps.

In the field of gripper and tool development, the data collected should be used to determine which systems are useful. In particular with the types of connections, it is shown that tools for loosening screw connections, for example, should work efficiently since these comprise over 80% of the connections. Further research could be done by developing flexible tools that allow the loosening of different connections to prevent time-consuming gripper changes. One approach could be multi-head tools, which Chen et al. already proposed for robotic disassembly [34].

5. Conclusion and Outlook

In this article, a concept has been developed to support the design planning of an automated dismantling system for LIB. The product analysis shows that the focus is on six dismantling processes and the handling of three different general shapes. Unfortunately, the detailed specification might differ considerably between the individual manufacturers. As long as there is no uniform design or cooperation for batteries, this point will remain a challenge in dismantling. A basic concept is derived to allow a flexible adjustment both in terms of quantity and variants.

In further work, the different modules of the packs should be examined to document the process spread and thus provide an indication for further development. The estimation of process times can also be investigated in this context. Also, detection and reaction strategies to uncertainties of the returned batteries need to be focused on further work. Finally, the development of flexible grippers should be intensified to ensure an efficient dismantling of an increasing number of batteries.

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