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Information Models for Automated Electric Vehicle Battery Disassembly: Integrating Domain Knowledge through a Multi-Faceted Data-Driven Approach

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Abstract

The widespread adoption of electric vehicles (EVs) necessitates effective end-of-life management strategies for their battery packs. When pursuing a recycling strategy to recover valuable materials such as nickel, manganese, cobalt, and lithium, the first step in most cases is to dismantle the battery at least down to module level. The state-of-the-art disassembly of EV battery packs relies on domain knowledge and is carried out manually for the most part. The potential hazards inherent in the dismantling process and increasing numbers of end-of-life batteries, coupled with a shortage of skilled workers, call for a safer and more efficient approach to dismantling than is currently the case. However, due to the high variety of end-of-life battery packs that return to recycling companies and their high system complexity, fully automating the disassembly process is not economically feasible. Therefore, the paper introduces an approach to extract and transfer domain knowledge from human experts to an accessible and structured information model. This model is intended to serve as the foundation for the development of disassembly assistance systems capable of aiding human operators during manual disassembly tasks and, in the long term, enabling the automation of critical disassembly steps. Furthermore, a theoretical concept for a disassembly station is proposed that allows a multi-faceted data collection process by providing a human-machine interface and multi-sensory equipment. This process encompasses detailed analysis of battery components, manual disassembly procedures, and expert insights. It aims at integrating, categorizing, and formalizing the collected data into a machine-readable format that captures both the procedural and semantic aspects of battery disassembly and enables the digital representation of the product and process.

Keywords: electric vehicle battery; disassembly; information model; domain knowledge

1. Introduction

The demand for resource efficiency and independence is leading the e-mobility industry to close material cycles and thus to open up new types of processes for material recovery [1]. For example, the EU Batteries Regulation specifies that the recycled content in the active material of battery cells must be 16% for cobalt, 85% for lead, 6% for lithium and 6% for nickel by 2031, and even higher by 2036 [2]. To achieve this, different recycling strategies have been developed and implemented in recent years, allowing end-of-life (EOL) battery packs to be disassembled to different levels (module, cell, electrode sheet), shredding the disassembly products if necessary, and separating and recovering the materials mainly via pyro- and hydrometallurgical processes [3].

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Dismantling, especially from pack to module level, is a process that is still carried out manually for the most part. However, manual disassembly poses a high risk to people and the environment: This is due on the one hand to the high system voltage of the battery packs, and on the other hand to the risk of fire from thermal runaways or the potential leakage of harmful chemicals if the battery cells are damaged or improperly handled. At the same time, the lack of personnel trained to work on high-voltage systems and the high process time of the manual disassembly process negatively impact the throughput of battery packs to be disassembled, which will become particularly evident when unit volumes will increase over the next decade. These factors motivate automation of the disassembly process, which in turn also faces major challenges.

On the one hand, there is a high diversity of variants in EOL battery packs due to constant further developments within the last few years and a lack of standardization of the battery design to date. On the other hand, battery packs are highly complex systems consisting of a large number of different components with various detachable and also non-detachable joints. Furthermore, EOL products can be in undefined and unknown states and especially recycling companies usually do not have any data about the products, such as CAD models. [4, 5]

Current research shows that rigid automation solutions cannot be used under the present conditions. In order to be able to react flexibly and adaptively to changing products, alternative approaches must therefore be applied [4]. In this research work, the approach of a disassembly assistance system for worker support as well as a hybrid, partially automated disassembly approach based on it are therefore pursued.

With established assistance systems, for example for manual assembly, the process is known in advance and the sequence of the individual steps and their execution is defined [6]. In disassembly, this knowledge must be acquired anew for each product variant. The efficiency of the manual process is therefore largely dependent on the experience of the respective disassembly specialist [7]. For the automation of individual process steps, an adaptive system is required that can intelligently and autonomously make decisions regarding the respective disassembly process [4, 8]. Intelligent systems require the basis of a sufficient amount of data on which they can learn appropriate decisions and strategies in advance. The creation of this data basis requires a high number of dismantled battery packs with sufficient variance and therefore currently appears unrealistic. [4]

Both the approach of the assistance system and the first steps towards an automated solution show that domain knowledge and experience in the field of disassembly remain indispensable. Consequently, a system must be developed that captures and formalizes this knowledge from humans so that it becomes readable and applicable for machines. In this paper, therefore, a concept for such a system will be presented. The approach aims at defining how knowledge can be extracted from the manual process which can then be used at a meta level to create automated process sequences and manual disassembly instructions in future works. In the following, first the scientific questions are defined, which have to be answered for the development of the system. Then, the results of various analyses on the product (EOL battery), the disassembly process and possible sources of information that can be integrated into the disassembly process are presented.

2. Problem definition

This research builds on the approach of Vongbunyong et al. [9]. In their work, they present a cognitive agent for automated disassembly that detects the individual components of the EOL product to be disassembled and tries different disassembly operations according to the trial-and-error principle until one operation is successfully performed. If these attempts fail too often, the agent requests human assistance. It stores the information gained from the trial-and-error process or from the human assistance in a knowledge database, which it accesses as soon as an already known product has to be disassembled. This process is shown in Fig. 1.

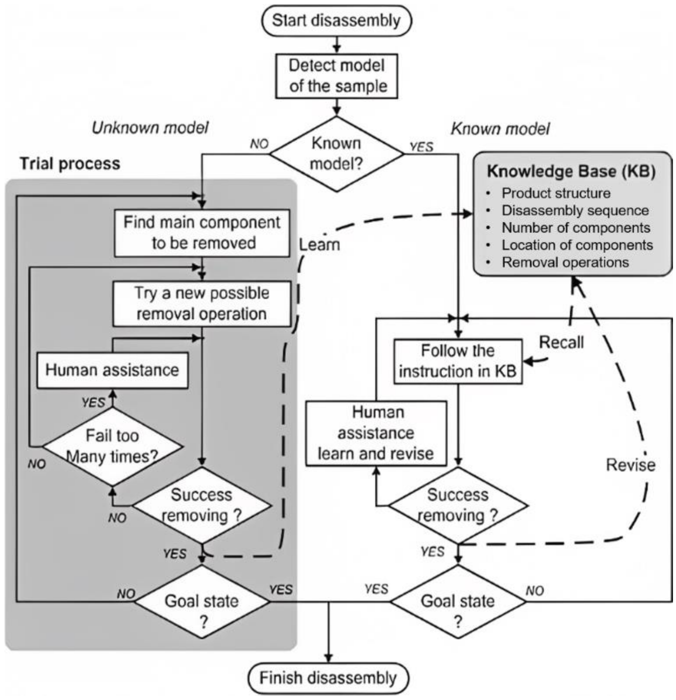

Fig. 1. Information processing in the cognitive agent [9]

Especially for highly complex and variant systems like battery packs, it is likely that the trial process for unknown product variants is a time-consuming endeavour. Therefore, this work proposes to replace the trial process with a manual process and to adapt the agent's learning behaviour so that the human is equivalent to a teacher and the agent is equivalent to a learner to whom the process is demonstrated by the teacher. This extension of the approach of Vongbunyong et al. [9] is shown in Fig. 2.

In order to develop such a transfer of domain knowledge from human to machine, the following questions need to be answered:

- What information is needed from the agent for disassembly so that it can mimic the process on its own?
- How can this information be linked together in an information model and made machine-readable?

- How can this information be obtained and how should sensor technology be combined?
- Derived from this, what does the design of a learning disassembly station for information acquisition look like?

The concepts used to answer these questions are presented below.

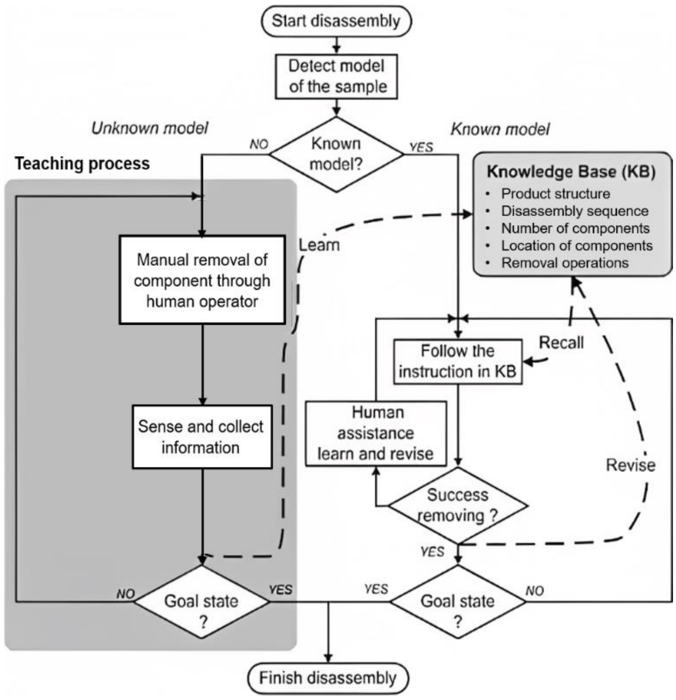

Fig. 2. Extension of the cognitive agent according to Vongbunyong et al. [9] by a teaching process.

3. Product and Process Analysis

In order to answer the first question about the required information, an analysis of the product, i.e. the EOL battery packs, and the disassembly process was carried out first. This approach only considers battery packs that have a module-to-pack design and whose modules can be removed from the system. Battery packs with a cell-to-pack or cell-to-chassis design or those in which the modules or cells are embedded in filler material were not considered. To this end, the disassembly of a Smart ForTwo battery pack was carried out by the researchers themselves, and literature describing the disassembly process for EOL battery packs was also examined.

Overall, the disassembly steps for the battery packs of the electric or hybrid vehicles Mercedes Plug-in Hybrid [10], Audi A3 Sportback e-tron Hybrid [11], Volkswagen Jetta Hybrid [12], Audi Q5 Hybrid [13], Smart ForFour [14] and Smart ForTwo were analysed. Despite the diversity of model variants and process routes, the analysis suggests that a basic set of operations needs to be performed for all packs under study. Furthermore, additional, individual operations must be performed for each model. These mainly include the disconnection of various electronic components such as the Battery Management System (BMS), the Cell Supervision Electronics (CSE), the Battery Junction Box or the Cell Management Controller and the respective cabling. Furthermore, the packs can be differentiated in terms of disassembly on the basis of the following points:

- Sequence of disassembly operations
- Placement of components in the pack, both absolute and relative to each other
- Appearance/design of the components

The operations and a list of the joints that have to be disconnected in the process are shown in Table 1 as an example for the battery pack of the Smart ForTwo. The operations that belong to the basic set of operations are highlighted.

Table 1. Disassembly operations for the battery pack of the Smart ForTwo

Operation	Joints
Electronic connections (connection for CAN bus, connection for service disconnect and high-voltage (HV) connection) - Unscrew frame	Screw joint
Cover - Remove nuts	Bolt joint
Cover - Remove screws	Bolt joint
Cover - Lift off	No connection
Remove busbars	Screw joint
Remove HV connector and service disconnect unit: • Unravel cable tie • Remove cover over service disconnect plug • Remove data cable with plug from connector • Remove several data cables from connectors	 Cable tie Geometry Plug with additional release mechanism in the form of a clip Plug without additional release mechanism
Remove the CSE boards: • Unplug CSE board • Unscrew CSE board	 Plug without additional release mechanism Screw joint
Remove cable harnesses	Connector with/without additional release mechanism Textile adhesive tape Cable tie
Remove CAN bus connector	Plug with additional release mechanism
Remove voltage sensor: • Remove wiring harness from voltage sensor support plate • Unscrew the voltage sensor support plate • Remove voltage sensor support plate	 Textile adhesive tape Screw joint Plug with additional release mechanism Geometry
Remove BMS: • Unscrew BMS • Loosen the connections of the BMS cable harnesses to the battery • Disconnect BMS main connector • Remove BMS	 Screw joint Cable tie textile adhesive tape Plug with additional release mechanism Geometry
Remove BMS carrier plate	Screw joint

Unscrew modules	Screw joint (low-lying)
Remove modules:	
• Detach module from cooling system	Bonding (thermal paste)
• Remove module	No connection

Despite the differences between battery packs and their associated disassembly processes, similar types of joints can be identified overall across all battery packs down to the module level, each of which can be disconnected using similar tools. An overview of these joints and their associated tools to disconnect them is given in Table 2.

Table 2. Battery pack joints and corresponding tools for manual disassembly.

Joint	Tool
Screw joint	Cordless screwdriver/ratchet with appropriate screw bit
Screw joint low-lying (e.g. between modules)	Cordless screwdriver/ratchet with extension and corresponding screw bit
Bolt joint	Cordless screwdriver/ratchet and socket wrench/screwdriver
Plug without additional release mechanism	Hand
Plug with additional release mechanism	Hand
Plug with additional release mechanism in the form of a clip	Hand and, if necessary, narrow slotted screwdriver
Cable tie	String cutter/scissors
Adhesive tape	Cutter knife
Bonding (e.g. by thermal paste)	Hand and crowbar
Geometric connection	Hand
No connection / part removal	Hand

Building on the previous analysis of the product and the disassembly process, the knowledge required to disassemble an EOL battery pack can now be specified. The required information can be divided into two groups. The first group contains the information on the structure of the battery pack, from which the sequence of part removal and thus the required disassembly operations can be derived. It also contains information about the individual components, such as the type of component or the material, so that the component can be assigned to an appropriate further processing operation based on this information after it has been disassembled. The second group contains all the information relating to the disconnection of the joints. This includes the type of joint, the position of the joint and the tools required to release the corresponding joint. Furthermore, the information on the tools can be supplemented by details on the loosening process, such as the force required. However, these are not absolutely necessary to be able to carry out the disassembly, but would rather represent limit or guideline values. The interface between the two information groups is represented by the information about which components are connected to each other by which joints.

4. Information Collection within the Disassembly Process

Subsequent to the definition of what information is needed to perform the disassembly, it is necessary to analyse which data sources are generally suitable for obtaining information from the disassembly process and, furthermore, which specific information can be obtained from which data source.

Three options for generating or providing data were selected as data sources: sensors, manual input and meta-information, e.g. in the form of a battery passport. The sensor technology can be further divided into visual data acquisition and tool monitoring. The choice of sensors is limited to data acquisition options that are already industrially established in assembly systems. If it turns out that the information that can be provided by these systems is not sufficient, other options must be considered at this point.

Which information can be obtained from which of the above data sources is listed in Table 3.

Table 3. Data sources in the disassembly process

Data source			Information
Sensors	Visual data acquisition	2D camera	• Tool used (derived from: type of joint) • Order of operations • Duration of operations • Worker position • 2D position and orientation of the tool • 2D position and orientation of the joint (if not hidden) • Type of joint (if not hidden) • Component type • Component condition • Battery pack type
		3D camera	• 3D position and orientation of the part • 3D position and orientation of the joint (if not hidden), allowing the generation of a 3D model of the battery pack
Sensors	Tool monitoring	Tool - Presence	• Tool used (derived from: type of joint) • Order of operations • Duration of operations
		Tool - Process parameters	• Depending on the tool and its sensor equipment, especially process forces
Manual input			• Missing information that could not be detected (e.g. material, type of component, condition of components, if not detected by sensor)
Meta-information			• Battery pack type • Electrical condition of the battery pack

It can be seen that the 2D camera offers the largest scope of potential information to be recorded. An extension from 2D to 3D vision, would allow a 6 degree-of-freedom localization of the parts or joints (3D position and orientation). In addition, a digital 3D model of the battery pack can be generated using the 3D camera. When recording visual data, however, it should be noted that information about the type and position of the joining joints or individual components can only be recorded if they are not obscured by other components. Furthermore, reliable classifications based on images, e.g. of components and joints, can only be made if a sufficient data basis exists in advance as a reference. In addition, classifications made using AI-based methods are always stochastic and non-deterministic, so classification statements potentially lack of certainty and interpretability. [15] In contrast, statements about the type and sequence of tools used as well as the duration of use can be made directly by checking the tool presence. In addition, further process parameters such as process forces or the rotational speed can be measured on individual tools, in the case of battery pack disassembly mainly on cordless screwdrivers, provided they are equipped with corresponding sensor technology. If information is still missing after data acquisition by optical sensors and tool monitoring, it can be supplemented by input from the operator. This can be done manually via a human-machine interface, for example. It is also possible to obtain information about the battery pack outside the disassembly process, which is referred to here as meta-information. An example of such a data source is the battery passport, the design and implementation of which is currently being driven forward by various initiatives [16, 17].

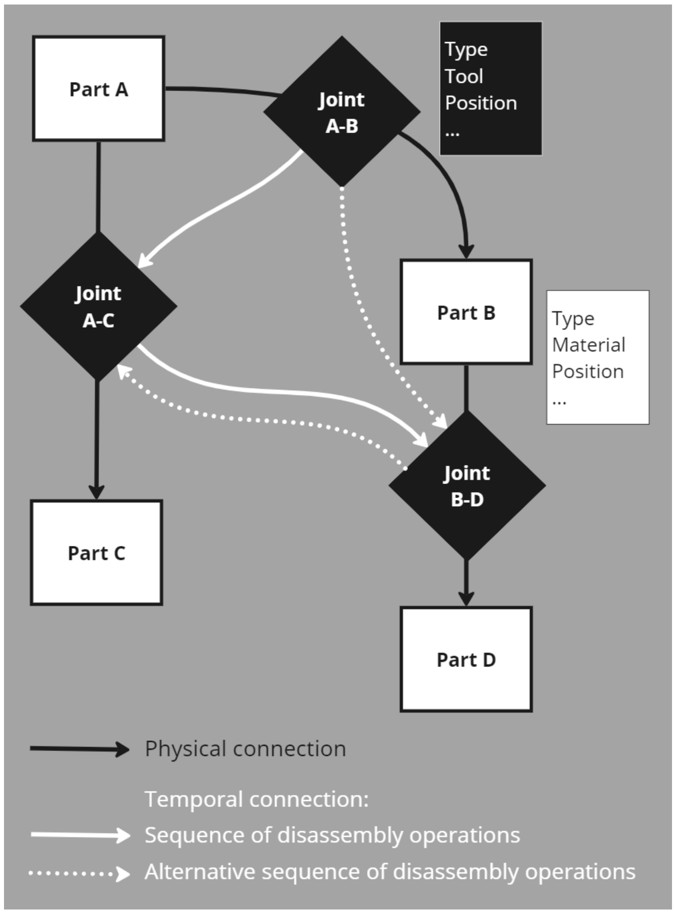

Fig. 3. Concept for a disassembly information model

5. Concept of the Information Model

All information collected during the disassembly process of a battery pack must be formalized and made available in a uniform way for each pack to enable further use in the form of work instructions in a disassembly assistance system or readability by machines for automation of individual process steps. Vongbunyong and Chen [9] describe a knowledge base for this purpose, which contains information about the battery pack and the disassembly process, but do not specify it further. For such a knowledge base, an information model is suitable in which all information required for disassembly can be structured and linked with each other. In the information model, both information groups, which are described in section 3 should be covered in the information model. For each battery pack, the information model is to be filled with data from the data sets identified in section 4. In this way, each individual disassembly process can be mapped uniformly despite the large number of variants of battery packs and disassembly operations.

Fig. 3 shows a basic design of such an information model. The basic structure of the model consists of two layers reflecting the two sets of information. The first level contains the information about the structure of the battery pack and corresponds to a graph whose nodes represent the components and whose edges represent the joint connections. For each node, i.e. each component, further details such as type, material and position are given. In this layer, the physical connection of the components is described. The second level, which is also represented in the form of a graph and overlays the first, contains all information about the disassembly process. Here, the joining connections correspond to the nodes and the disassembly operation to the edges. In addition, information on the required tool, position of the joint and, if necessary, other process parameters is given for each node. This level reflects the chronological relationship, i.e. the sequence of the disassembly operations and, depending on the design of the edges, can also contain different, alternative disassembly paths.

Furthermore, the graph-based information model can be linked to a 3D model of the battery pack generated using the 3D camera to visually represent the information and enable a visual comparison between digital information space and reality.

6. Conclusion and Outlook

In this work, the question of what information is required for the disassembly of a battery pack was investigated. After analysing different battery packs and their disassembly processes, it was found that the information can be divided into two groups, one regarding the structure and the other regarding the disassembly operations. Despite the diversity of variants, repetitive or similar operations could be identified across all packs. Furthermore, the question was answered which information sources exist within the disassembly process and how the corresponding information can be obtained. Finally, the concept of an information model was presented, with which this information can be formalized and mapped uniformly.

Based on this and to bring the theoretical concept of the multi-faceted data collection for information modelling to reality, it must now be investigated which sensor technology is specifically suitable for data acquisition. In addition, a data pipeline must be designed that makes it possible to structure the recorded information and store it in the information model at the appropriate points. For instance, this could be done by structuring the product-process relations by using graph-based approaches like Disassembly Petri Nets or AND/OR graphs. Especially for the visual data, algorithms for image processing like segmentation and feature extraction (e.g. edge detection, texture analysis) have to be designed and implemented, since the information from image data cannot be provided directly. Finally, it must be further investigated how the information can be retrieved from the information model and used for dismantling when a known pack that has already been analysed is to be dismantled in a disassembly assistance system or with the aid of a (partially) automated solution and if the approach contributes to minimizing operating times and reducing physical and cognitive workload for human workers.

7. Acknowledgements

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