Robot Assisted Disassembly for the Recycling of Electric Vehicle Batteries

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Abstract

The rising number of electric vehicles (EV) will eventually lead to a comparable number of EV batteries reaching their end-of-life (EOL). Efforts are therefore being made to develop technologies and processes for recycling, remanufacturing and reusing EV batteries. One important step of many such processes is the disassembly of EOL EV batteries, which poses a challenging task due to unpredictable lot sizes and volumes, as well as significant variations in battery design between different car models. In response to these challenges and the increasing demand, we present a concept for a battery disassembly workstation where a human is assisted by a robot. While the human performs the more complex tasks, the proposed robot performs simple, repetitive tasks such as removing screws and bolts. Such a robot requires 1) a suitable procedure for the unscrewing task, 2) a means of autonomously changing screwdriver bit in accordance with the variety of screws and bolts found in EV batteries, and 3) some means of acquiring information regarding the location of these fasteners. This paper summarises the results of our preliminary investigations.

Keywords: disassembly, electric vehicles, traction batteries

1. Introduction

Advancements in lithium ion (Li-ion) battery technologies have increased the practicality and attractiveness of electrically-driven vehicles (EV), leading to an increase in their development and production, as well as that of Li-ion batteries. Despite of this, the problem still remains to develop a truly sustainable method of dealing with these batteries at their end-of-life (EOL). One possibility is to give EOL EV batteries a second life as stationary energy storage [1]. Another alternative is to recycle the EOL batteries to recover raw materials for the production of new batteries.

One possible recycling process is that proposed by the German project consortium "LithoRec II – Recycling of Lithium Ion Batteries II". The first step of this recycling process is the discharging of the batteries, in order to reduce the danger associated with the high voltages (up to 400 V). After discharging, the batteries are disassembled, before being subject to a coarse shredding. Subsequently, the shredded material is dried and freed of ferromagnetic materials before being subject to a fine crushing. This crushed material is then separated into a light fraction, consisting of the separator membranes, and a heavy fraction, containing various metals. Raw materials are obtained after further treatment of both fractions. The objective of the project, by realizing this process, is to gain high-quality secondary raw materials that can be used in the production of new batteries or other industrial products, hence closing the materials cycle for lithium ion batteries. The focus of this paper will be on the second step of the aforementioned process chain: disassembly, i.e. the separation of discrete components from the product. Disassembly allows the battery cells to be separated from the other structural and connecting components for the subsequent processes, and is desirable for maintaining the high quality of the recovered raw materials. Disassembly is only viable if components can be separated without excessive costs or risks. Since the battery cells contain substances hazardous to human health (e.g. the electrolyte) one must ensure that cells are not damaged during disassembly.
Due to the many product variants, the non-existent standards in battery design and the fact that the detailed designs of the batteries are generally unavailable to the recycler, EV batteries are currently manually dismantled. However, where labour costs are high, disassembly is one of the most expensive steps in the proposed recycling process. On the other hand, fully automated disassembly is also infeasible to implement at this time, due to the many product variants and relatively small volume of each variant. Furthermore, at a product’s EOL, components and fasteners may be damaged and therefore more difficult to remove. These challenges are generally not present in assembly processes where automation is common-place. In order to meet these challenges, we propose a hybrid human-robot workstation where the robot executes the simpler, repetitive tasks, alongside a human that handles more complex tasks and is capable of reacting to problems where they occur.

One possible task for the robot is the removal of screw and bolt fasteners, which we will refer to as unscrewing. Many variants of EV batteries are held together by a large number of screws and bolts. Unscrewing is a relatively simple task that is repetitive and uninteresting for a human. The potential for robots to take over this task has been previously recognised. [2] describes work on a robotic system for unscrewing, where the inaccurate visual localisation of screws was compensated for by using a tool specifically designed for unscrewing. This tool used compliance and mechanics that caused the screwdriver tip to move in a spiral-shaped search pattern if the tool initially fails to engage with the screw head. [3] describes a system for unbolting car wheels, whereby an active stereo vision system was used for the detection of screws. A “special unbolting tool” was used, along with a force-torque sensor and task planning module, to perform the physical disassembly. The detection algorithm provided a 98% detection rate, and used contour analysis and the Generalised Hough Transform to identify bolts arranged in the expected circular pattern. This was followed by template matching to PCA-generated eigentemplates for more precise localisation. [4] describes a multi-sensory robotic system capable of unscrewing and removing the CD drive from a PC and the electronic circuit from a toy. This was achieved using a combination of visual servoing and force control. In order to detect screws in camera images, an edge image was obtained, followed by the polygonal approximation of contour segments using the Douglas-Peucker algorithm and template matching. These systems demonstrate that the detection and eventual removal of screws by a robot is an achievable task. [5] describes work on the vision system for the robotic unscrewing of ceiling beams during interior office renovations. The ceiling beams were first localised; template matching was then used to generate hypotheses for screws located on the beams. A support vector machine (SVM) subsequently reduced the number of false positives. The authors hypothesise that highly robust screw detection can be achieved by integrating the information from multiple images along the beam. However, these preliminary calculations assume that it is equally likely to detect any screw (and reject any non-screw), which is not the case in reality. [6, 7] approached the problem of the camera-based detection of Phillips head screws by applying the Haar Cascade [8], a method utilising a decision tree that classifies each region based on easily-calculated Haar-like features. Despite a very promising detection rate (98%) achieved on the training set, this significantly decreased (to around 64%) when applied to actual objects of disassembly; false positives also occurred due to similar light reflections on scene objects. Low-resolution images (ranging from 10x10 to 15x15 px) were used, such that the cross shape of the Phillips head was basically unrecognisable in the training images.

This paper provides a summary of the work and insights gained so far in the area of robot assisted disassembly in the LithoRec II project. Section 2 examines the steps required in the disassembly of EV batteries. This leads to the conclusion that an appropriate degree of automation for the disassembly of EV batteries is currently a hybrid human-robot system, whereby a robot assists a human worker by taking over the task of unscrewing. Section 3 provides an overview of the proposed system setup. This is followed by the results of our initial investigations in Section 4, and finally the conclusions that can be drawn.

2. Disassembly of EV batteries

Since the technology and design of EVs is still developing, no common standards in EV battery design have yet been established. Consequently, many design variations exist. One reason for this is that most car manufacturers only make small changes to their conventional cars in order to make them electrically driven. This means that the battery is designed to fit in an already-existing car body and not vice versa. Therefore, the design of EV batteries differs not only from manufacturer to manufacturer, but also from car model to car model. Nevertheless, there are some basic steps that are required for the disassembly of a battery system. These are:

1. Opening of the battery system, i.e. removal of the cover
2. Cutting of the electrical connections between the battery modules and the electronic components
3. Removal of the mechanical connections between the system components (modules, electronics) and the battery base
4. Removal of the electronic components
5. Removal of the battery modules
6. Disassembly of the battery modules and removal of the battery cells

In order to provide an example of the detailed operations required for the disassembly of a battery system, we refer to a case study of the Audi Q5 Hybrid battery system (for more detail, see also [9]). Due to its use in a hybrid EV (HEV), the Audi Q5 Hybrid system is a relatively small system with dimensions of about 50 cm x 70 cm x 15 cm and a weight of about 35 kg. The battery system mainly comprises four battery modules, a battery management system (BMS) and the necessary power electronics. The four battery modules/stacks each contain 18 battery cells connected in series. The main parts of the Audi Q5 Hybrid battery system are shown in Fig. 1 and Fig. 2, where they are labelled with a number later used for reference.
The detailed disassembly steps of the manual disassembly of the Audi Q5 Hybrid battery system and modules are listed in Table 1 and Table 2. The analysis of the disassembly steps shows that many handling and unscrewing operations are necessary, especially with regard to the disassembly of the modules. The handling operations, in particular the separation of components, often require high manoeuvrability and varying forces and techniques. Since the required techniques are highly dependent on the design of the product, the automation of these tasks was deemed to be prohibitively difficult and costly. On the other hand, screws and bolts are standardised components and can be removed using the same technique. Unscrewing is a relatively simple technique that has been automated previously and has widespread application in the disassembly of EV batteries. Hence, it seems worthwhile to implement the task of unscrewing on a robot that assists a human worker.

Table 1: Disassembly steps for the Audi Q5 Hybrid battery system

| Step no. | Disassembly step                                      | Necessary tool       |
|---------|-------------------------------------------------------|----------------------|
| I       | Unscrew covers (1), (6) and casing bottom (12)         | Screwdriver          |
| II      | Removal of the power electronics cover (1) and the side covering (2) | Hand                 |
| III     | Disassembly of the live lines from the modules/stacks (14) | Screwdriver          |
| IV      | Cutting of the cable ties (3)                         | Side cutters         |
| V       | Disassembly of the plug connection between the cell controllers and the BMS (4) | Hand                 |
| VI      | Removal of the BMS (4) and power electronics (5)       | Hand                 |
| VII     | Cutting of the bus for the thermo sensors              | Side cutters         |
| VIII    | Disassembly and removal of the system cover (6)        | Screwdriver, hand    |
| IX      | Unscrew and removal of the cable guiding (7)           | Screwdriver, hand    |
| X       | Removal of the gas venting (8) and the cover of stacks (9) | Hand                 |
| XI      | Disassembly and removal of the connectors between the stacks (10) | Screwdriver, hand    |
| XII     | Unscrew and removal of the stack holders (11)          | Screwdriver, hand    |
| XIII    | Removal of the casing bottom (12)                      | Hand                 |
| XIV     | Unscrew and removal of the stack fastener (13)         | Screwdriver, hand    |
| XV      | Removal of stacks (14)                                 | Hand                 |

Table 2: Disassembly steps for a module of the Audi Q5 Hybrid battery system

| Step no. | Disassembly step                                      | Necessary tool       |
|---------|-------------------------------------------------------|----------------------|
| I       | Unscrewing of the nuts on the cell contacts (15)       | Screwdriver          |
| II      | Removal of the cables (16) and the cell connectors (17)| Hand                 |
| III     | Unscrewing and removal of the side covers (19)         | Screwdriver, hand    |
| IV      | Removal of the battery cells (18)                      | Hand                 |

3. The hybrid human robot workstation

For the robot-assisted disassembly of the EV batteries, we propose a workstation concept as depicted in Fig. 3. Both the human and the robot require access to the disassembly object, i.e. the battery. To minimise system complexity and the time required to frequently transport the disassembly object...
between separate workspaces, we propose for the human and the robot to share a common workspace. Furthermore, the human and robot also require access to their own disassembly tools. For the human this may be a variety of tools including pliers, screwdrivers, a hammer and cutting tools. For the robot this consists of different kinds of socket wrench bits for its unscrewing tool (not depicted in the figure). The human carries out more complex tasks such as prying apart components joined with snap fits or (to a limited extent) glue, and pulling out or cutting cables, while the robot unfastens all screws and bolts. The location of the screws and bolts can be either taught manually or detected via a camera. In the figure this is indicated by a sketch of a camera with its field of view on the battery.

The robot for such a workstation should, on the one hand, be lightweight to reduce the risk associated with collisions. On the other hand, the robot should have a sufficient load capacity and be able to compensate for the forces and torques generated from handling an electric screwdriver and loosening screws. One robot that fulfils these criteria and that we use for our work is the KUKA Lightweight Robot (LWR). The LWR is a 7 degree-of-freedom robot arm with torque sensors in each joint. By means of its internal control algorithms, the stiffness of the robot can be adjusted. Set to very low joint impedance, the LWR compensates only for the weight of its own joints and tool, allowing a human user to physically position the robot by hand to teach new positions or motions.

The robot tool consists primarily of a subassembly of a commonly available cordless electric screwdriver, including the DC motor and chuck. This subassembly has been modified and mounted on the robot flange (see Fig. 4). Fixed to the chuck is a hex-to-square adaptor suitable for attaching common socket wrench bits. As described in [10], a mechanism has been designed that enables the robot to change socket wrench bits autonomously (see Section 4.2). The torque and rotational speed of the screwdriver can be controlled by adjusting the motor current via a microcontroller.

4. Unscrewing with the robot

For the implementation of the proposed robot, several challenges have to be met. In addition to the task of unscrewing itself, this robot should also be able to change its unscrewing tool autonomously according to the many different types of screws found in battery systems. Finally, the robot must also know or be able to acquire the locations on the product at which to unscrew. Our initial investigations into these areas are presented in the following subsections.

4.1. The unscrewing task

The task of unscrewing using the robot can be summarised in the following steps:

1. Set the tool up with the correct bit, if necessary.
2. Move the tool/bit to a location that is appropriate for approaching the fastener head. Methods of determining fastener location include using a database, visual feedback, or demonstration by hand.
3. Engage the bit with the fastener. This may be achieved using some combination of visual feedback, compliance and/or searching motions. [2] suggests that the screwdriver should be rotating with a slower speed (30-40 min⁻¹) during this stage to ensure correct engagement.
4. Turn the fastener anti-clockwise until it is separated from the product. [2] shows that speed has little effect on the torque required to remove a screw and suggests a high rotational speed of the screwdriver during this stage to minimise disassembly time.

In order to perform this task, the robot must first know the location of the screw to be removed. Since detailed product specifications are generally not available to the recycler, it is impractical to assume that exact locations will be available via a database or CAD models. Hence, it is desirable to acquire the locations of fasteners at the point of disassembly. Unskilled workers are generally employed for disassembly to minimise costs. Therefore, only methods that do not require high technical expertise of operators can be considered. Two potential methods of acquiring this information are:

1. User demonstration: users intuitively add to the system’s knowledge or database by physically demonstrating this knowledge on the product at hand.
2. Detection: the system identifies and localises fasteners autonomously using cameras or similar technology. In this case, a significantly higher rate of errors is expected.
A system can take advantage of both options if it has basic detection capabilities, but resorts to human demonstration in the case of undetectable fasteners. Initial investigations regarding both options are presented in the following sections. The option of user demonstration was first explored with the implementation of the bit changing mechanism, in which the user physically moves the robot’s end-effector to the correct location to teach the location of the bit. Preliminary results regarding the camera-based detection of M5 bolts are further presented.

4.2. Bit changing

A bit changing mechanism was designed that allows the robot to use common socket wrench bits without any actuation other than that of the robot itself (further details in [10]). The robot can directly retrieve a bit from the main slot of the bit holder (see Fig. 5). Above this, a notch wider than the hex-to-square adaptor and narrower than the smallest socket wrench bit allows the robot to separate the bit from the robot tool. An external computer controls the robot motion, treating tasks as finite-state machines. Motion control is described within the states. The robot’s in-built Cartesian and Joint Impedance options were central to the approach. Using this methodology, the robot was generally capable of retrieving and returning socket wrench bits of different sizes to the bit holder after a “demonstration” by the user. During this demonstration, the robot is set to very low joint impedance, where it is free to be moved and only compensates for the force of gravity acting on its joints. The user physically moves the robot to an appropriate position to approach the bit. Once the demonstration is complete, the robot tests this information in an attempt to engage with the bit; the user observes this procedure, and can stop and reposition the robot if necessary. Due to the control strategies and the compliance of the robot, this method was found to be tolerant to some position/orientation error in the human demonstration, as well as the arbitrary rotation of the bit within the bit holder.

Fig. 5. Bit holder for the bit-changing mechanism [9]

Since the task of engaging with a screw or bolt has similar physical requirements (approach in tool axis direction; detecting when the surface has been reached; searching motions in case of inaccuracy) as that of operating this bit changing mechanism, the majority of procedures used in implementing the bit changing task are directly transferable to the task of unscrewing. The main additional element required for robotic unscrewing is the ability to detect when the unscrewing procedure is completed or has failed. The main drawback in using physical demonstration to teach the location of each fastener is the time required for the human to correctly position the robot. On the other hand, physical demonstration is also useful for teaching the robot appropriate joint configurations.

4.3. Camera-based detection of screws

The approach used by [6, 7] was trialled for the camera-based detection of screws, since the Haar Cascade implementation is open source and freely accessible in the OpenCV library (available at http://opencv.org/). We hypothesised that the reported false positive rate could be improved by

- Using higher resolution in the positive training set, and
- Using images from disassembly (particularly examples of false positives) in the negative training set.

A Haar Cascade was trained on a training set consisting of manually-cropped images of the M5 bolts on the contacts of the Q5 battery module; images obtained from Google Images searches on keywords such as battery, cables, aluminium and casing; and random images cropped from photos taken during disassembly that do not contain screws. During preliminary testing on new images from the disassembly environment, incorrectly-classified regions were additionally added to training set, from which updated classifiers were trained.

In order to estimate the minimum required resolution of the training set, a brief experiment was undertaken to investigate our colleagues’ recognition abilities at differing resolutions. The negative samples in this test consisted of regions labelled as false positives by the classifier. Sample images were resized if necessary (to lower resolutions only) and shown as normalised grayscale images. The results from 21 respondents are shown in the receiver operating characteristic (ROC) graph in Fig. 7. The true positive rate (TPR) describes the proportion of correctly-recognised bolts, whereas the false positive rate (FPR) describes the proportion of negative (non-bolt) images that were falsely identified as bolts. While some error can be attributed to human error (e.g. an accidental click), it is clear that with the given image quality, some regions in the disassembly environment can also be mistakenly classified by a human when taken out of context. Without contextual information or the integration of multiple images, it is unlikely that computer vision techniques would be able to provide better accuracy.

Fig. 7 suggests that our colleagues’ TPR begins to decrease as resolution falls from 20 px to 16 px. Hence, the Haar Cascade was subsequently trained using positive sample images of size 20 x 20 px. To test the performance of this method, a test set was formed by removing a random selection of 500 positive images and 500 negative images (400 from the disassembly environment and 100 random images) from the
training set. A new classifier was trained using all images excluding those in the test set. 1000 positive and negative images were used at each training stage, out of a total of 2266 positive and 3209 negative images.

A ROC curve can be generated by sequentially removing layers from the cascade [8]. The performance results in Fig. 8 were generated by running the OpenCV function CascadeClassifier::detectMultiScale() on all images in the test set. A positive identification is taken if the algorithm identifies any screw in the test image (positive images only contain one screw) and a negative if no screw is found.

Since the desired outcome is for there to be a point close to the top left-hand corner (where all images of bolts are correctly classified as bolts, and no bolts are identified within the negative training set), this result is worse than desired. To be able to detect 50% of the screws, there is over 50% chance for there to be some false detection within an image. This is due to the difficulty of the test set, and because the negative test images (commonly larger than 100x100 px; up to 8 MP) are significantly larger than the positive test images (20x20 px). With the given method, this causes results to be skewed, as a false positive may mean that the algorithm has yielded correct negative results on the majority of an image but failed in one area. Future work involves gathering results based on the number of times the algorithm is applied. Sufficient resolution for human recognisability does not imply ease of recognition using computer vision methods. Since Haar-like features are not inherently skew and rotation invariant, separate training sets may be required to effectively use Haar Cascades for different viewing angles. Controlled lighting conditions may also aid in accuracy.

5. Conclusion

The rising number of electric vehicles and hence the rising demand for lithium ion batteries has led to an increasing interest in the recycling of EOL batteries, of which disassembly can be an important part. Using an illustrative example, we proposed a hybrid human robot workstation for the disassembly of lithium ion batteries where the robot has the task of unscrewing. For this purpose, we have developed a bit changing mechanism for the robot, and investigated two options by which the robot can acquire location information: physical demonstration and the camera-based detection of bolts. The results suggest that physical demonstration may be feasible for obtaining the location of fasteners, however has the drawback of time consumption. Automatic detection can speed up this process, however further work is required to implement an algorithm with sufficient accuracy.

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