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RESEARCH

Robotics for electric vehicles battery packs disassembly towards sustainable remanufacturing

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Abstract

The automotive industry is involved in a massive transformation from standard endothermic engines to electric propulsion. The core element of the Electic Vehicle (EV) is the battery pack. Battery pack production misses regulations concerning manufacturing standards and safety-related issues. In such a fragmented scenario, the increasing number of EVs in circulation is growing exponentially, opening new challenges for managing the End-of-Life (EoL) of their battery packs. This paper analyses the use of robotics for EVs' battery pack disassembly to enable the extraction of the battery modules preserving their integrity for further reuse or recycling. The analysis highlights that a complete automatic disassembly remains difficult, while human-robot collaborative disassembly guarantees high flexibility and productivity. The paper introduces guidelines for designing a robotic cell to disassemble a battery pack with the support of an operator. The design of the workcell evaluates the technological requirements for disassembly, the analysis of potentially explosive atmospheres (ATEX) of the area around the battery pack, and the design and optimisation of robotics tools in the ATEX zone. The work proposes solutions according to the current international standards.

Keywords Battery packs end-of-life · Battery packs reuse and recycling · Battery packs disassembly · Circular economy · Robotics for waste treatment · Robotic disassembly

Introduction

Context

The EVs market is growing fast, setting new records year by year. According to the Global EV Outlook 2023 of the International Energy Agency (IEA) [26], the number of EVs globally reached 26 million in 2022 with an increment of 60% relative to 2021, reaching 10 million

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of sales (6 million only in China) in a year. The 14% of new cars sold globally in 2022 were electric, from 9% in 2021 and 5% in 2020; the percentage reached 21% in Europe and 29% in China. The growth is confirmed in the first quarter of 2023; the increment of sales was 60% in the United States, 20% in China and 10% in Europe if compared to the same period of 2022. The forecasts anticipate an acceleration of the EVs penetration of passenger and light-duty vehicles in the next years [30]; IEA [26] foresees 14 million of sales in 2023, reaching 18% of total car sales in the year.

During the last two decades, the Li-ion Batteries (LiB) technology prevailed over others [55, 67]. Their strengths are high specific power, low self-discharge, long cycle life, no memory effect and wide temperature range of operation [7]. Soon, LiB will continue to dominate the market, albeit several new technologies are emerging. The automotive sector mainly uses the architecture pack-module-cell to build battery packs, where cells are grouped in modules and modules are grouped into a pack. The cells can have three shapes: small solid cylindrical cells, large solid prismatic cells, and large soft pouch cells [70]. Most EV manufacturers are currently using prismatic cells for their performance in terms of thermal management with a wide surface for heat exchange and simplified geometry. Recently, some manufacturers have proposed the solution pack-cell to simplify the architecture and improve performance.

It is well known that battery pack recycling is a valuable activity that can bring to the recovery of secondary raw materials [40]. In 2019, the estimated recycling rate of LiB was only 5-7% [43]. At the international level, the legislation relative to battery recycling and reuse is fragmented and mainly oriented to recycling instead of reuse and remanufacturing [42]. The current recycling techniques could be more efficient regarding the percentage of secondary raw material recovered and are highly energy-consuming. The reuse and the remanufacturing is poorly investigated yet [16], even if it can be a viable alternative for second-life applications exploiting the remaining storage capacity of the cells [11], such as storage devices for renewable energies [6]. Whether to proceed with recycling or reuse, the battery pack must be sorted, discharged and disassembled [20]. Proper sorting and disassembly will significantly impact the effectiveness and quality of the following phases [58]. Current battery packs are not designed to be disassembled, spaces between modules are narrow, and joint technologies are mostly irreversible (e.g., glued parts, welded plates, one-way screws), bringing to a difficult non-destructive disassembly. Standards for building the packs are missing, introducing significant shape, dimensions, and module layout variability. Despite a decade of EV battery production, safety standards are the only ones in place for testing before market entry [7]. As an additional remark, it is difficult to recover information on battery pack life (e.g., the technology, the number of charges or the number of kilometres travelled by the vehicle), limiting an objective analysis of the pack status and a proper EoL treatment. This leads to extensive manual labour for battery pretreatment (such as sorting, discharging, and mechanical disassembly), posing high risks to operators and increasing the cost of recycling/reuse processes. The current industrial approach is unsuitable for large-scale treatment but works for a limited battery flow handled primarily by car dismantlers. The absence of legislation is evident in the practices of car dismantlers, who heavily rely on manual labour and treat batteries as electronic devices. Operators typically follow basic safety protocols using electrical Personal Protective Equipment (PPE), focusing solely on the risk of electrocution. The lack of a diagnostic system limits the module analysis to evaluate the reuse. After the disassembly, modules are mostly sent to comminution [60], to prepare the material for a further chemical treatment to recover a set of valuable materials. At the same time, automation is generally poorly adopted due to the lacking of solutions and the limited investment capacity of car dismantlers, which are frequently SMEs with a low acquaintance with automation. On the contrary, such solutions could be more suitable for battery manufacturers, who can easily access product information and treat their products with limited variability. Regarding safety aspects, LiBs may be subjected to internal failure due to electrochemical system instability; the risk is related to safety accidents associated with continuous heat and gas generation causing a mechanical rupture and ignition of the combustible materials. The damage to the cell structure can derive from mechanical abuse (e.g., external body penetration), thermal abuse (e.g., overheating) and/or electrical abuse (e.g., short circuit) that can generate side effects and bring to the thermal runaway phenomenon [7]. The battery discharging is also crucial because the Battery Management System (BMS) prevents over-discharging the cells, so battery packs, even after discharge, will have a residual charge during the disassembly.

The high development rate of battery technologies makes it challenging to follow adequate regulations. One of the first tentative is the new EU Battery Regulation [13], which applies to all batteries sold in the EU independently from the production technology, entered into force in August 2023 and began to apply in February 2024. The regulation explicitly focuses on LiB setting EoL management obligations and product traceability. The Battery Digital Passport will become mandatory for all batteries with more than two kWh. All batteries must have QR codes reporting relevant information such as material composition, rated capacity, original power capability, expected lifetime expressed in cycles, etc[1]. The regulation also imposes that battery producers must prepare their products for reuse, repurposing and remanufacturing such as easily allowing repair operations and providing a reset function for the battery software. The new EU Batteries Regulation is expected to become the global benchmark, surpassing comparable regimes regulating battery EoL, sustainability and safety. There are also initiatives at the international level for the Battery Identity Global Passport [3]. One of the most important is the public-private collaboration Global Battery Alliance (GBA) [18], which brings together the most important batteries and cars manufacturer with public institutions, and which one of the scopes is the Battery Passport program.

The management of battery packs EoL can significantly benefit from standardisation enabling an effective circular economy around these products [20]. Standards and battery redesign [39] could simplify adopting automatic systems for testing, evaluation, and eventually, disassembly enabling the reuse and the product remanufacturing, improving operators' safety and increasing the overall process efficiency [61].

Motivation and contribution

The pack-to-module disassembly is a fundamental step for the treatment of modules which should be started for the recycling or reuse of separating modules from the other components (e.g., the metallic frame, wires, plastic hoses, and electronic board). To date, no relevant plants are dedicated to this scope; in most cases, EVs and their EoL management follow the same stream of standard vehicles. A network of car dismantlers collects EVs by removing the battery pack from the car without applying specific procedures, mostly with manual operations without getting information about the device. This approach is not expected to change in the following years, and the effects of standardisation (not foreseen yet) for battery production will be visible in a mid-term period.

This work aims to analyse the pack-to-module disassembly operations, evaluating all the risks related to the task. Subsequently, guidelines for semi-automatic disassembly are introduced according to the current safety standards. Due to the high flexibility required for the task and the high variability of the products, using industrial robots is a viable solution

[1] see Annex XIII of the regulation [13].

instead of designing dedicated machines. For this reason, the work focused on the design of robot tools proposing an optimised number of tools to limit the costs and the complexity of the solution to spread the solution as much as possible, even to SMEs, as car dismantlers, with low investment capacity and reduced knowledge of robotics and automation. To date, most of the scientific production on the topic addressed laboratory experiments with collaborative robots, which are inadequate to the scope and need to apply an accurate safety analysis of the task [38].

The testbed was a Stellantis 500e MY 2022 battery pack equipped with a Samsung SDI battery pack (Low Range "LR" version). Due to the possible risk related to the thermal runaway, it was applied the standard of explosive atmospheres using the IEC 60079-10-1:2020[2] [25]. Following the recommendations given after the safety analysis, as a specific potentially explosive atmosphere (ATEX)[3] zone, the battery pack was manually disassembled. The manual disassembly brought to a disassembly procedure which was decomposed and analysed to identify how to automate the same operations with a robot. The guidelines of robot tools design involved (i) the reduction of tools number, (ii) the use of technologies compatible with the ATEX zone and (iii) flexibility of the solution applicable for a large number of use cases.

The paper is organised as follows: Section 2 analyses the related works, Section 3 describes the experimental setup, the ATEX zone classification and the Stellantis Fiat 500e "Low Range" battery pack disassembly steps. Section 4 discusses the guidelines for designing a robotic cell for disassembly. Finally, Section 5 reports the conclusions and the future works.

Related works

This literature review focused on battery pack disassembly through automatic machines, privileging robotic solutions.

The interest in using robots for disassembly devices at their EoL has become increasingly important in the last few years [41]. Robotic disassembly involves several research topics such as Task and Motion Planning (TAMP), robot tool design, and robot sensor-guided motion. Battery pack disassembly is a part of this field of applications as a practical approach to preserving operators' safety and health by coping with the high variability of products [38, 64]. However, most authors agree that a fully automatic battery pack disassembly is not feasible with the current constraints [17, 21, 37, 41, 56]. For some operations, complete automatic solutions might lead to increased dismantling costs, making automation uneconomic [4] (e.g., manipulation of non-rigid components).

The study of human-robot hybrid disassembly cells was also evaluated [17, 22, 48] and modelled by optimising the number of workstations, the workstations' idle time, the number of workers and the disassembly costs [59]. The use of collaborative robots is also a valuable alternative [41, 48, 56, 68] to designing collaborative applications for practical human-robot cooperation [17, 57]. On the contrary, some disassembly operations require medium-high payload robots [31], such as manipulating modules which can weigh tens of kilograms.

The disassembly operations require a high-level decision capability to define the proper treatment of the disassembled part [44] reflected on the high autonomy of the robotic system in Task Planning (TP) to enable a practical disassembly without human intervention [8].

[2] "Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres"

[3] The acronym derives from the French "appareils destinés à être utilisés en ATmosphère EXplosive" equivalent to "equipment intended for use in explosive atmospheres".

Due to the high variability of the products, rigid scheduling with robot pre-programmed operations is not a viable solution to the problem. The operator's presence in collaborative disassembly brings increasing complexity imposing a dynamic TP to effectively assign tasks to the robot or to the operator [21]. Using the disassembly matrix [56] allows to formally describe the connection and the priority relationships between components. The search for an optimal disassembly sequence in the solution space is an optimisation problem that can be solved with different optimisation algorithms [2, 32]. Addressing complex operations such as separating joined parts (e.g., plates joined with sealing and mastic) requires cooperation between at least two robots, with one robot handling the part and the other separating the parts [15] introducing multi-robot motion planning problem. The definition of an ontology, with partial destructive rules, allows to the generation of a disassembly sequence inferring a feasible plan [62]. NeuroSymbolic computing was applied to TAMP to address robotic bolt removal [65].

The use of machine vision is also a relevant aspect of coping with the variability and the lack of information on the products. Furthermore, flexible objects such as wires and hoses can be in unpredictable position [5]. To improve the effectiveness of the solution, multiple vision systems are necessary to detect and locate the elements to be disassembled [69]. A mixed-use of 3D and 2D vision technologies is valuable for detecting and classifying the parts. 3D systems are used for the location of the entire battery pack and robot guidance with the drawbacks of higher computational load w.r.t. a 2D system [5]. Instead, 2D systems help to detect and classify internal parts such as modules, wires, connectors and screws [36]. Deep Learning techniques are frequently applied for image processing for object classification and detection [8, 36]. Additional perception technologies, such as the X-Ray Fluorescence (XRF), can be used to distinguish parts compositions [69].

The design of robot tools is a crucial aspect of the disassembly task in general [22, 37]. It is frequently the need of designing custom tools for specific operations [1, 10, 31] and multiple tools are anyway necessary to address all the disassembly operations of the battery pack. Early works focused on manipulation and testing [46], even if a broader range of operations are necessary, as cutting (e.g., wires and hoses) [31], unscrewing [1, 57] and joint separation. Machine learning can support the disassembly operations by processing the data collected from the robot tools providing information on the ongoing process. An interesting example is the analysis of the torques required by an electric screwdriver for unscrewing that can bring to detect non-detachable stripped screw [1]. Recently, from the perspective of collaborative applications, the design of a soft pneumatic gripper was also evaluated for small object manipulation, safe human interaction and good adaptability with multiple shapes [10].

As a drawback, the scientific literature mainly addresses laboratory test cases with low industrial relevance without considering critical aspects such as safety issues related to the explosive atmosphere, while it is well known that LiB can be subjected to thermal runaway [19], which can lead to cell rupture, fast temperature rise, with the emission of a mixture of toxic and flammable gases [34, 47, 63]. The flammable gases, if ignited, can cause fire and explosion. The harsh conditions that can bring to thermal runaways, such as short-circuiting, crushing and overcharging can easily happen during the disassembly [9, 33]. Some works discuss the safety systems as fire extinguishing agents [35, 66] for LiB. Monitoring devices must be installed alongside the fire extinguishing systems to prevent and contain risks [33]. The most common are temperature sensors, infrared cameras for non-contact temperature measurement and gas sensors specifically designed to detect the gas mixture released by LiB after thermal runaway [23]. The combination of sensors and models to predict the thermal runaway was also studied and evaluated to prevent and mitigate the phenomenon [47].

Several research projects are ongoing bringing the research results to the industrial level. At the European level the Horizon Europe projects Rhinoceros [54], Rebelion [52], Recirculate [53], the UK project ReLiB [51], the German regional projects DemoBat [49] and the Italian regional project EcoCirc [50], among the others, have the scope to develop solutions based on automation and robotics for the non destructive disassembly of battery packs in the perspective of reuse and remanufacturing.

Materials and methods

The approach followed in this work starts from the battery pack manual disassembly. Once the disassembly procedure was completed, the disassembly steps were compared with the known disassembly procedure reported in the literature, trying to identify a generalisation of the disassembly operations. The automatable steps were defined, identifying suitable technologies compatible with the automatic disassembly according to the restrictions given by the potentially explosive atmosphere.

Risks and safety issues related to battery packs disassembly

Before proceeding with the manual disassembly, the risks related to the potentially explosive atmosphere (ATEX) were evaluated by classifying the area around the battery pack. As reported in [14], even using modules with a limited residual charge, thermal runaway, with gas emission, is possible in case of short circuits that can easily happen during the disassembly. The gas mixture released from LiB can create an ATEX zone around the battery pack.

The reference standard is the IEC 60079-10-1:2020 dedicated to "the classification of areas where flammable gas or vapour hazards may arise and may then be used as a basis to support the proper design, construction, operation and maintenance of equipment for use in hazardous areas". The analysis involves environments, appliances or systems prone to forming explosive atmospheres; to determine areas with a different probability of risk and adopt suitable measures for each dangerous area to avoid or decrease the risk of explosion. The classification of the ATEX zone into zone 0, 1 and 2, which qualify the probability of having an explosive atmosphere, need to be done for each source of emission and depend mainly on three factors: the degree of the emission, the degree of ventilation, and the availability of ventilation. The data used in this work to classify the ATEX zone around the battery packs, according to the international standard IEC 60079-10-1:2020, are reported below.

Table 1 Technical specification of the environment where the disassembly cell operates, data are used for classifying the ATEX zone

Parameter	Value
Size of the environment LxWxH [m]	24.7x12.2x9
Type of the environment	Closed
Atmospheric pressure [Pa]	101325
Room temperature [$^\circ C$]	25
Ventilation	Natural
Availability of ventilation	Adequate
Velocity of the ventilation [m/s]	0.05
Ventilation efficiency	3

Table 2 Technical specification of the battery pack, data are used for classifying the ATEX zone

Parameter	Value
Producer	Samsung
Nominal energy $[kWh]$	44
Nominal voltage $[V]$	408
Module shape	Prismatic
Battery type	Lithium-Nickel-Manganese-Cobalt (NMC)
Number of modules	9
Cells configuration series/parallel	96s/2p

Environment and ventilation: the space available for the experiment is an industrial building, with the specifications reported in Table 1.

During the disassembly, it was assumed that only one module at a time could be subjected to a short circuit with a consequent thermal runaway, so in these conditions, only the cells contained in the module were the source of the gas release.

Battery type: the battery used for the real experiment was a Stellantis Fiat 500e MY 2022 equipped with a Samsung SDI battery pack Low Range "LR" version; during the ATEX zone classification, it was considered a most conservative case using the battery pack of a Stellantis Fiat 500e High Range "HR" version, the technical specification is reported in Table 2.

To determine the mixture of gases (in terms of type and percentage of each gas) released by an NMC LiB after the thermal runaway, it was considered what is reported in [63].

Degree of emission: the degree of emission represents the probability that a source can emit gases into the atmosphere; the data used to classify the ATEX zone around the battery pack are reported in Table 3.

The secondly emission grade means that it is not expected an emission in the ordinary operation of the process equipment. Still, the emission can only occur occasionally and for short periods, e.g. following a fault.

Results of ATEX zone classification: using the data reported in Tables 1, 2, 3 and applying the standard IEC 60079-10-1:2020 considering a single module as the source of the release, with secondly emission grade, an adequate ventilation, and a medium dilution grade from the Table D.1 of the standard it is possible to classify the area around the source of the emission

Table 3 Technical specification of the degree of emission data is used for classifying the ATEX zone

Parameter	Value
Type of the emission	Gas emission
Degree of emission	Secondly
Pressure $[Pa]$	101325
Temperature $[°C]$	25
Safety factor	0.5 (secondly emission)

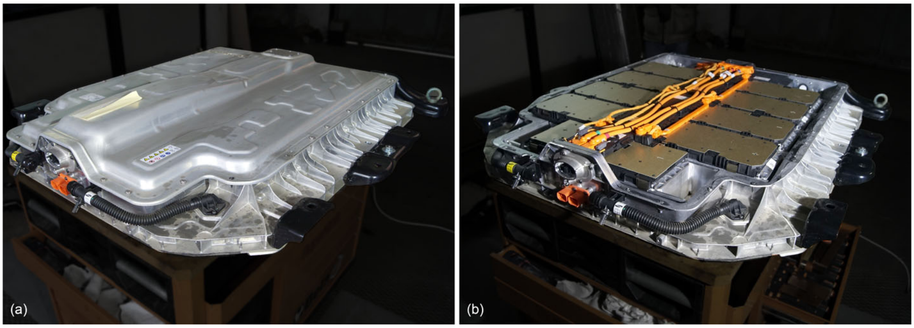


Fig. 1 Stellantis Fiat 500e MY 2022, Low Range “LR” version, Samsung SDI battery pack before disassembly (on the left), and after upper cover removal (on the right)

as Zone 2[4]. The explosive atmosphere, classified as Zone 2, is the sphere with a radius 1 $[m]$ with the centre in the centre of the source of emission. All devices in this area must be with the ATEX certification equipment group IIC and temperature class T1. As an additional safety measure, an industrial aspirator can be installed close to the battery pack to collect gases that can be present inside the battery pack before removing the covers.

Materials

As mentioned, a battery pack was assumed to be a use case for manual disassembly. The donor vehicle for the presented case study is a Stellantis Fiat 500e MY 2022 equipped with a Samsung SDI battery pack (Low Range “LR” version), see Fig. 1.

The battery pack was purchased directly from Stellantis and was provided with the *so called* “green” classification, meaning that the pack was inside a vehicle which was not subjected to any crash or accident and then removed by the factory still in safe and correct working conditions, Table 4 reports all the specification of the battery pack used for the experimental part. The cell composition is 60% Nichel, 20% Manganese, 20% Cobalt cathode and a graphite anode. Figure 2 reports the principal components (see Fig. 2a) of the Stellantis Fiat 500e MY 2022 “LR” battery pack with their relative quantities in Fig. 2c, while the components of the modules (big and small) are highlighted in Fig. 2b with their relative quantities in Fig. 2d.

The battery pack used for the real experiments was slightly different from the Stellantis Fiat 500e High Range “HR” version used for the ATEX classification, which is bigger in terms of capacity, the choice was anyway conservative because the ATEX zone classification used more severe conditions.

Regarding PPE, during the manual disassembly in every step of the disassembly procedure, the operator wore rubber-soled shoes, safety glasses, electrically insulated gloves rated at 1000V AC (wore in combination with another pair of protective gloves) and cotton clothing with no exposed metal components. When operating on the battery pack, the operator stood over a high-voltage insulated blanket rated at 1000V AC. The battery pack itself was placed and fastened over an insulated surface. The equipment used to operate on the modules or components under tension were tools compliant with the IEC 60900:2018 [24] regulation

[4] The definition of Zone 2 is a hazardous area classified as an atmosphere where a mixture of air and flammable substances in the form of gas, vapour or mist is not likely to occur in regular operation, but if it does occur, it will persist for a short period only.

Table 4 Technical specifications of Stellantis Fiat 500e equipped with a Samsung SDI battery pack (Low Range "LR" version)

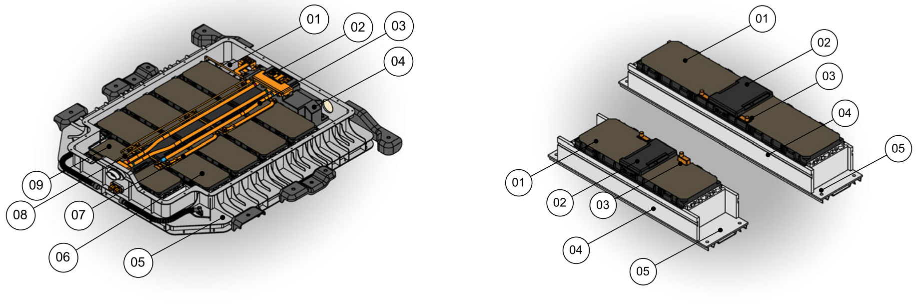
Battery pack technical specifications	
Parameter	Value
Size LxWxH [mm]	1211x1157x182
Module shape	prismatic
Weight [kg]	176
Cells configuration series/parallel	108s/1p
Nominal energy [kWh]	23.8
Nominal system voltage [V]	396
Working temperature [$^\circ C$]	$-30 \div 60$
Number of modules	5 (1 small + 4 big)
Small and big module technical specifications	
Parameter	Value
Small module size LxWxH [mm]	587x173x143
Big module size LxWxH [mm]	817x173x143
Small module weight [kg]	16.7
Big module weight [kg]	30.3
Small module cell configuration series/parallel	12s/1p
Big module cell configuration series/parallel	24s/1p
Small module nominal energy [kWh]	2.66
Big module nominal energy [kWh]	5.3
Small module nominal voltage [V]	44.04
Big module nominal voltage [V]	88.08

and rated up to 1000V AC and 1500V DC. The equipment used when working on mechanical components, not directly under tension, but anyway included inside the ATEX Zone 2 area (sphere of 1m in radius with origin in the centre of the battery pack) were spark-proof tools certified under European Directive 2014/34/EU [12]. During the whole disassembly procedure, no power tools were used, and all the jacking and lifting devices employed during the whole process were manually operated hydraulic systems. During the disassembly, the battery pack was monitored with an infrared camera to measure the temperature.

Method: manual disassembly of automotive battery packs

The manual disassembly was conducted to preserve the components' integrity for reuse and remanufacturing, avoiding destructive disassembly strategies. All the images and descriptions are referred to the Stellantis Fiat 500e MY 2022, Low Range "LR" reported in Fig. 1. Figure 3 reports on the CAD model of the battery packs some key points (see Fig. 3a) necessary for the disassembly with their descriptions (see Fig. 3b). The battery pack's standard position is the car's mounting position.

Before disassembly, the battery pack was inspected to identify damages, and the infrared camera was installed to monitor the temperature. The battery pack was discharged to the



(a) (b)

ID	Description	Quantity
01	Battery Pack Management System (BPMS)	01
02	Fuse box	01
03	High-voltage wiring harness	01
04	Battery Disconnect Unit (BDU)	01
05	Battery pack frame	01
06	Module (big)	04
07	Bus bar	07
08	Wiring harness	01
09	Module (small)	01

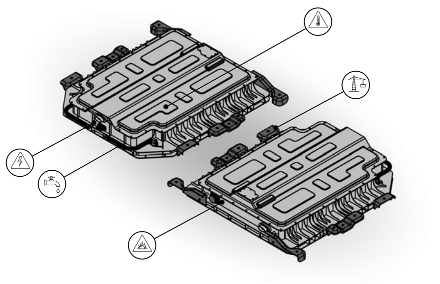
(c)

ID	Description	Quantity
01	Cells (inside)	12/24
02	Combined Charging Unit (CCU)	01
03	Terminal	02
04	Cell carrier aluminium structure	01
05	Cooling plate	01

(d)

Fig. 2 In Fig. 2a are highlighted the main components of the Stellantis Fiat 500e MY 2022 "LR" battery pack with their quantities in Fig. 2c. The components of the modules (big and small) are highlighted in Fig. 2b with their quantities in Fig. 2d

lower limit allowed by the BMS. After draining the cooling liquid from the cooling circuit through a liquid aspirator, the battery is ready for mechanical disassembly. Figures 4, 5, and 6 visually reports all the steps for the mechanical disassembly, the balloon callouts refer to the components described in Fig. 7. The first operation is the removal of the fuses, which requires a plate opening; see Fig. 4a. The tasks of this step are unscrewing, metallic plate manipulation, and fuse manipulation. The second step is the upper cover removal; see Fig. 4b. The cover is screwed and sealed on the main frame with mastic; after removing the screws, the cover separation from the frame requires a combined action of multiple tools as a spatula,

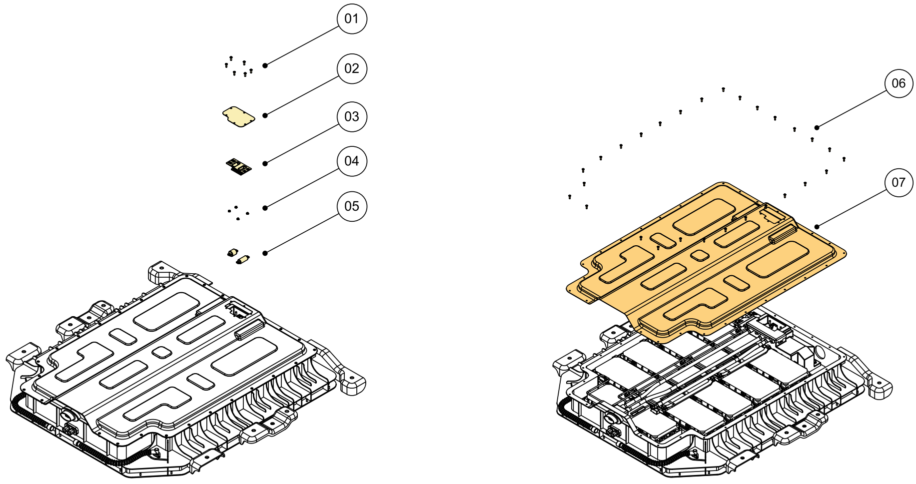


(a)

ID	Description
	Battery pack temperature level measuring point
	Battery pack lifting point
	Explosive gasses detecting point (venting port)
	Battery pack cooling system draining point
	Battery pack charging level measuring point

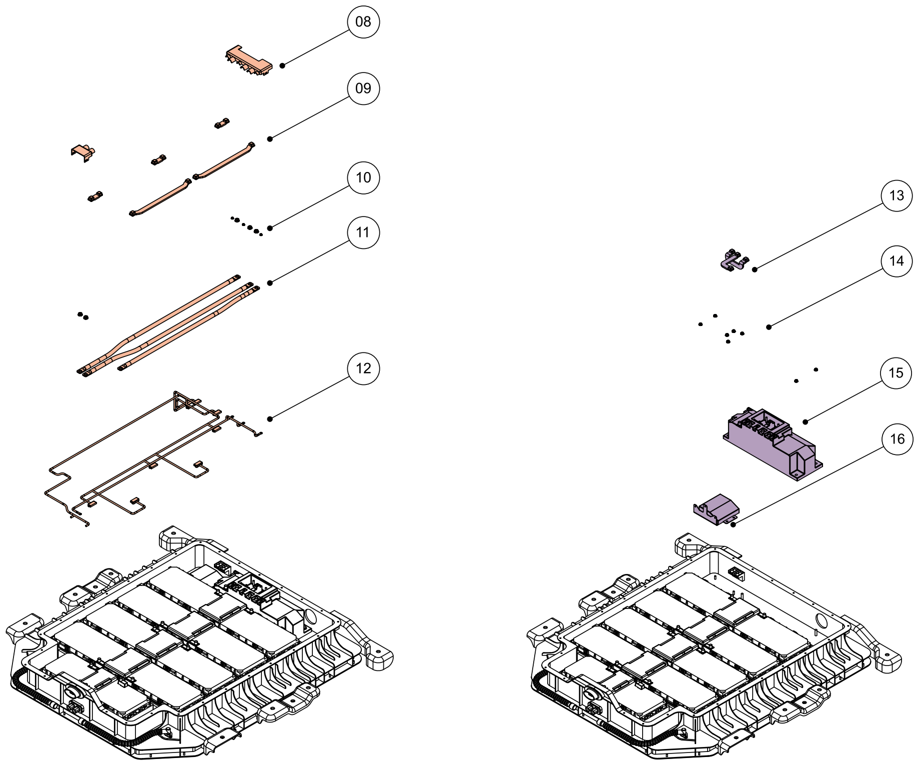
(b)

Fig. 3 CAD model of the Stellantis Fiat 500e MY 2022, Low Range "LR" version, the key points useful for the disassembly are highlighted in Fig. 3a with their description in Fig. 3b



(a) Fuses removal (b) Upper cover removal

Fig. 4 Detailed disassembly steps for the fuses and the upper cover removal



(a) Wires removal (b) BMS removal

Fig. 5 Detailed disassembly steps for the wires and BMS removal

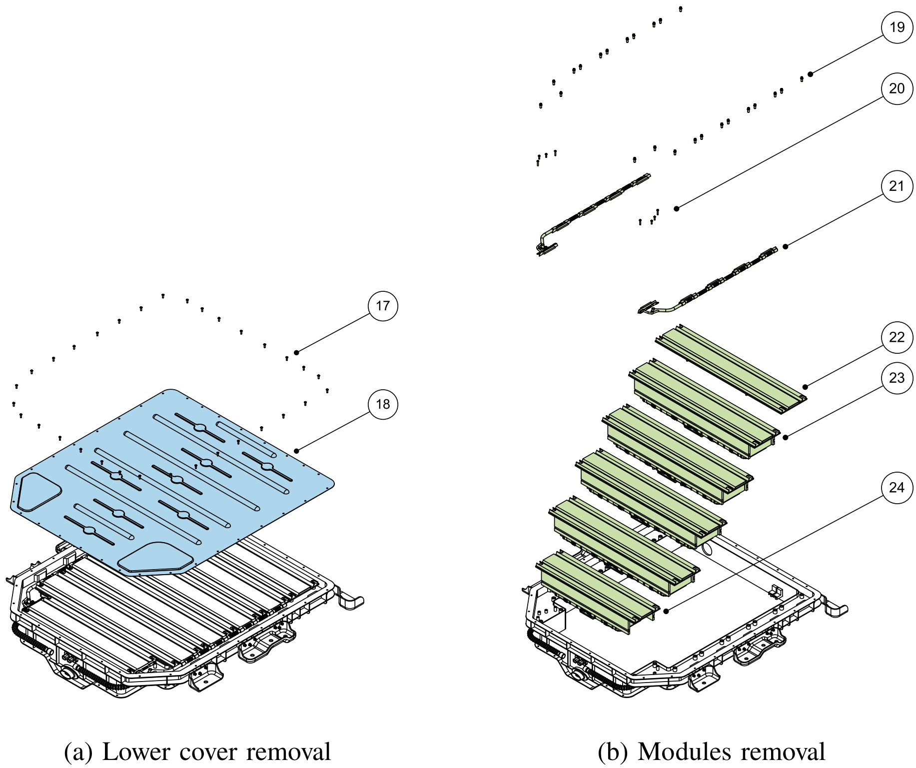


Fig. 6 Detailed disassembly steps for the lower cover and modules removal

wedge, and crowbar, while keeping a proper pulling force on the cover avoiding parts stick again after separation. The tasks of this step are unscrewing, cover manipulation and plate separation. The third step is wiring removal; see Fig. 5a. Plastic belts that keep wires fixed must be cut, connectors unplugged, and the fastening system removed before removing the wires. The tasks of this step are cutting plastic ties, unplugging and manipulating connectors, unscrewing and manipulating flexible wires.

The fourth step is the BMS removal; see Fig. 5b. The fastening systems must be removed and the BMS parts extracted. The tasks of this step are unscrewing and parts manipulation. The fifth step is removing the lower cover; see Fig. 6a. Operations are the same as upper cover removal; the battery pack need to be rotated 180° before removing all the screws that fix the cover to the main frame, then follows the cover separation from the frame, as for the second disassembly step, is required a combined action of multiple tools as a spatula, wedge, crowbar while keeping a pulling force on the cover avoiding parts stick again after separation. The necessary tasks are unscrewing, cover manipulation and plate separation. The sixth step, and the last, see Fig. 6b, foresees modules extraction from the frame. The battery packs need to be rotated at 180° as in the fifth step, the fastenings released, and cooling hoses removed to free the modules. Modules need to be separated from the frame breaking the sealing silicone. The necessary tasks are unscrewing, hoses manipulation and module manipulation.

ID	Description	Quantity
01	M5 screws	06
02	Fuse box lead	01
03	Fuse box insulating cover	01
04	M8 nuts	04
05	Fuses	02
06	M5 screws	28
07	Battery pack top lead	01
08	Insulating covers	02
09	Bus bars	05
10	M6 nuts	08
11	High-voltage wiring harness	03
12	Wiring harness	03
13	Bus bars	02
14	M6 nuts	08
15	Battery Disconnect Unit (BDU)	01
16	Battery Pack Management System (BPMS)	01
17	M5 screws	28
18	Battery pack bottom lead	01
19	M8 screws	24
20	M4 screws	06
21	Cooling lines	02
22	BDU and BPMS plate	01
23	Module (big)	04
24	Module (small)	01

Fig. 7 Detailed description of the disassembly steps for the Stellantis Fiat 500e LR. The numbering is referred to the phases reported in Figs. 4, 5, and 6. For each element, the quantities are reported

Guidelines to design a robotic cell for battery packs disassembly

As already mentioned, it was considered the use of industrial robots instead of custom disassembly machines to keep as flexible as possible the solution. The reasons are multiple: designing a custom machine for a specific battery pack is not economically sustainable, mainly when the disassembly is in charge to car dismantlers who must treat a wide range of battery packs with unpredictable features, quantities and order. Custom machines do not foresee human-machine workspace sharing and tend to be designed for complete process automation.

The disassembly steps described in Section 3.3 were analysed to evaluate which steps are suitable for automation and which are not. The disassembly procedure was also compared with those reported in literature [21, 31, 48, 56], finding a substantial equivalence in the operations required for the disassembly. The design avoided using destructive disassembly techniques, such as cutting saws, to foster the reuse of components and to cope with the ATEX Zone 2 classification of the disassembly area.

Table 5 reports the macro-categories of tasks in which the disassembly steps can be grouped; Table 5 also reports the risk for the operators associated with the task and the possible issues coming from the automation of the task. Seven macro-categories were identified; only three of them are partially automatable, or rather, automation can be less effective than human intervention in terms of flexibility, time spent on the task, and hence the economic sustainability of the application. The three tasks are plastic ties, connectors and cooling hose removal. Plastic ties are commonly used to fix wires and hoses, frequently placed manually, with a certain degree of uncertainty, and tightly attached to wires or hoses. Plastic ties need to be cut, and they can't be recovered. An operator can be faster and more effective on a lighter and less risky task compared to the other.

In the case of connector removal, it is necessary to have high dexterity to release the retaining latch and, at the same time, pull the connector. Moreover, the high variability of components (see Fig. 8) is a barrier to creating an automatic general solution; based on that, even in this case, an operator is more effective than the automatic solution. Due to the

Table 5 List of disassembly tasks grouped into macro-categories, for each task it is specified which can be automated and the possible issues coming from the automation

Task	Risks for operators	Automatable	Issues for automation
Fasteners removal	highly repetitive task	yes	presence of one-way screws; presence of damaged fasteners; presence of rust and thread locker; need fasteners position detection
Sealed part separation	heavy dangerous	yes	multiple types of mastic, silicone, glue, etc...; parts stick together again after separation; need multiple tools at the same time; need multiple robots
Plastic ties removal	no	partially	presence of permanent joints need position detection
Electric connectors removal	electrocution	partially	need complex and coordinated actions; required high dexterity; extreme variability of connectors; need position detection
Cooling hoses removal	no	partially	need complex and coordinated actions; required high dexterity; manipulate flexible elements need position detection
Manipulate rigid parts	heavy electrocution ergonomics	yes	presence of semi-rigid elements; extreme variability of parts (i.e., weight and size); parts made with multiple materials; need position detection
Manipulate flexible parts (wires and hoses)	electrocution ergonomics	yes	manipulation of flexible elements; extreme variability of parts; parts made with multiple materials; unpredictable position and shape; need position detection

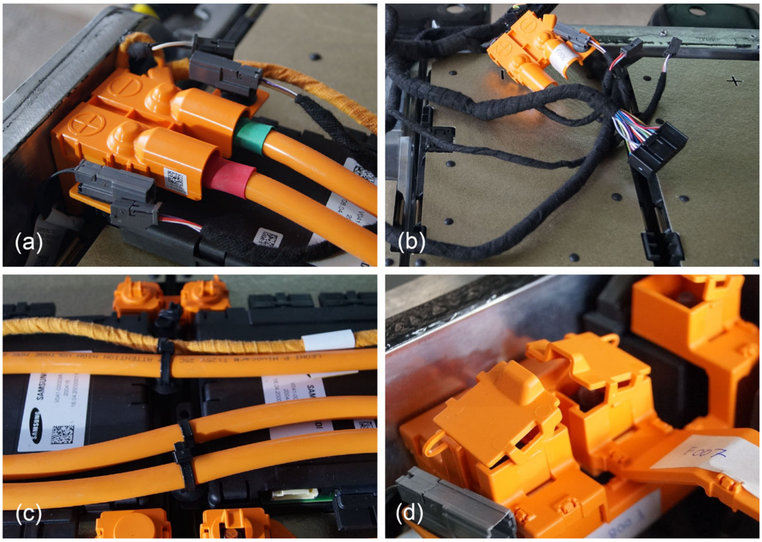


Fig. 8 Example of connectors found in the Stellantis Fiat 500e "LR" battery pack

low value of connectors, cutting the wires to avoid connector recovery can be an alternative solution to automate the removal of the wires. Finally, as for electric connectors, cooling hoses need to be removed; even in this case, all the observations made for connectors are valid, and manual removal can be a feasible alternative. Plastic hose cutting is a viable alternative to achieve the same result with a robot. The other four tasks can be automated, relieving the operator from severe and dangerous activities.

Separating sealed parts, such as the upper and lower cover from the main frame, requires the combined action of at least two tools handled by two robots. One robot handles passive/active mechanical tools such as wedges, crowbars, spatulas, etc.; a second robot works in coordination to exert force on the part to be removed and avoid sticking the piece again.

The number of fasteners in a battery pack is relevant. The automation (e.g., the upper and the lower covers of the Stellantis Fiat 500e LR have 56 bolts to be removed) can bring benefit by relieving the operator from a highly repetitive task. The main barrier to automation is the fasteners detection that imposes the use of vision systems.

Part manipulation is also a challenging task; the parts to be manipulated are highly variable and made of multiple materials that can be rigid and also flexible (e.g., wires and plastic hoses). Grippers need to be able to pick heavy elements such as modules or BMS that can weigh tens of kilograms and small and light objects such as fuses, busbars and plates. Operators can benefit from automation, avoiding lifting high weights with a bad posture and the risk of electrocution and module explosions. Also, in this case, parts need to be detected using a vision system.

Robot tools optimisation

Given the tasks macro categories reported in Table 5, four types of tasks were identified corresponding to the same number of tools necessary to the robot for the disassembly. The same tool can be realised with different approaches and technologies. Table 6 reports the

Table 6 List of possible tools to address a specific task

Task	Tool	Technology	Pros	Cons
Unscrewing	impact wrench	pneumatic	simple; cheap	difficult torque control
		hydraulic	relatively cheap; accurate torque control; high power-to-weight ratio	piping
		electric	accurate torque control	expensive
Sealed part separation	wedge spreader	hydraulic	high separation force	piping
	wedge spatula crowbars	mechanical	simple; cheap	need actuation force; limited by the robot size
Parts handling	two-finger grippers	pneumatic	simple cheap	difficult to control fingers position
		hydraulic	relatively cheap; easy and precise control	piping
		electric	easy and precise control	expensive
	vacuum gripper	pneumatic	simple and reliable; compliant with ATEX zone; cheap	limited force; need planar surfaces; need high volume of air
	adhesive gripper	Van der Waals forces	simple and reliable; cheap; compliant with ATEX zone	limited force need planar surfaces
	electromagnet	electric	simple and reliable; cheap; high forces	works only for electromagnetic materials
Cutting wires and hoses	shear	pneumatic	simple; cheap	difficult to control; limited force; need special blade to operate in ATEX zone
		Hydraulic	relatively cheap; easy and precise control; high power-to-weight ratio	piping; need special blade to operate in ATEX zone
		electric	easy and precise control	expensive; need special blade to operate in ATEX zone

Each tool's available technologies are reported with pros and cons to facilitate the choice. Where not explicitly declared, the devices must be certified as ATEX devices if they need to operate in the area Zone 2 as reported in Section 3.1

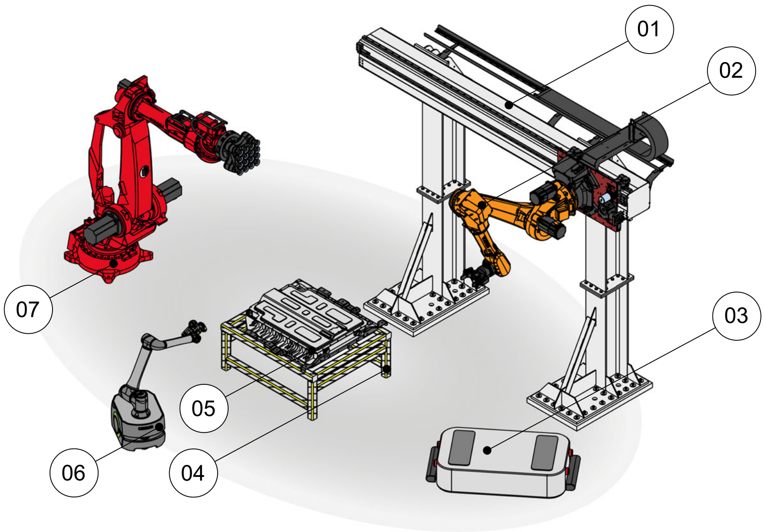
four families of tasks derived from Table 5 associated with the possible type of tools and the viable technologies with their pros and cons. For electric connectors and cooling hoses removal, defined as partially automatable in Table 5, it was decided to dedicate a cutting tool to cut wires and hoses. Adopting this tool does not preclude operator intervention from detaching electric connectors, preserving the integrity of the wires and the cooling system hoses.

The four tools families are impact wrench, passive/active spreaders, shears, and grippers to manipulate parts. Regarding fasteners, all the cases analysed (both from the battery pack under examination and the cases in the literature) present screws and bolts. The tool dedicated to fastener removal is an impact wrench; the choice was driven by the possible presence of rust and thread locker that impose high torque to remove the screws. As reported in Section 3.1, all the tools operating in the sphere with radius $1[m]$ with the centre in the emission source must be certified as devices compliant with ATEX Zone 2 group IIC and temperature class T1. It is worth noting that the ATEX certification (see Section 3.1) for tools such as impact wrenches, wedge spreaders and shears is not sufficient for the device itself. Still, the certification must be extended to the tools' accessories. The accessories mounted on the impact wrench need to be spark-proof (e.g., made with Copper-Berillium alloy), as for the wedge and the shear blades. In particular, shear blades need to be realised with non-conductive materials (e.g., ceramic) to avoid the electrostatic charges generated by the sliding between blades, and the metal of the wire can produce sparks.

Disassembly robotic cell

The disassembly robotic cell reported in this section was designed applying the guidelines described before. The cell, reported in Fig. 9, is equipped with two industrial robots, one with a medium payload (R1) mounted on a linear axis to improve the workspace, and the second is a medium-high payload (R2). An Industrial Mobile Manipulator (IMM) works as a mobile inspection system and a picking system for small parts. Due to the number of tools required by the disassembly, see Table 7, R1 and R2 must be equipped with a quick coupling system for robot tool change.

R1 is responsible for unscrewing screws and bolts, separating sealed parts, such as the upper and the lower cover, and cutting wires, busbars, and hoses when the user decides not to preserve their integrity. The choice of a pneumatic impact wrench was motivated by the high availability of ATEX devices with a limited cost, high reliability and high torques suitable in case of rusted bolts or with the presence of thread locker; pressurised air is available in most industrial plants with simple connections. The wedge spreader and the shear are hydraulic with a high power-to-weight ratio; both devices are portable with a compact hydraulic power pack supplied by a $48[V]$ battery mounted on the robot tool. This solution avoids complex piping through the robot tool change system. Generally, it is rare to find wedge spreaders and shear with ATEX certification due to the wedge and the shear blades that need to be realised with non-conductive materials; custom solutions must be adopted. R2 is responsible for parts handling; the robot has two different handling tools: a two-finger gripper to manipulate heavy parts, such as the modules, and a vacuum gripper to pick lighter planar elements as covers. R1 and R2 must work together for part separation, as the upper and lower cover are removed, using the wedge spreader (R1) and the vacuum gripper (R2) simultaneously. The IMM has a single two-finger gripper to pick small parts, such as fuses, plates, hoses, wires, etc. The IMM also works as a mobile inspection system by bringing on its tool an infrared camera and gas sensors close to the area in which the disassembly is ongoing. The battery pack is



ID	Description
01	Actuated linear rail for Robotic Arm 01 lond distance placement
02	Robotic Arm 01 (medium payload)
03	Autonomous mobile platform for battery pack and fixture handling
04	Battery pack supporting and handling fixture
05	Battery pack
06	Inspection mobile robot (industrial mobile manipulator)
07	Robotic Arm 02 (medium-high payload)

Fig. 9 CAD model of the disassembly robotic cell (currently under development) and the elements description

placed on a mobile platform able to tilt the pack during the disassembly and move it outside the cell in case of emergency (i.e., thermal runaway and gas emission).

Additional 2D and 3D vision systems are mounted on the tools of R1 and R2 to detect the element in the battery pack. Figure 9 reports a 3D model of the disassembly cell and a description of all the elements; the real cell is still under development.

Regarding human-robot collaborative applications, the reference Technical Standard is the ISO/TS 15066:2016 [29][5]. Standard non-collaborative robotic cell foresees the use of safety fences segregating the robot workspace. Access to the segregated area is limited through doors locked with safety locking devices or optical barriers where the operator's entrance triggers an emergency stop. This approach is unsuitable for a robotic cell, where human-robot workspace sharing is necessary, and the operator must enter the robot workspace, bringing lower productivity. Speed and separation monitoring is one of the four methods introduced by the standard ISO 10218-1 zISOTS:10218sps1sps2011 foreseen for human-robot collaborative operation. The ISO/TS 15066:2016 defines the speed reduction rules for collaborative operations where contact is not allowed. The operator's position must be tracked through safety monitoring systems such as 2D laser scanners or 3D radar sensors.

[5] the ISO/TS 15066:2016 was introduced to supplement the requirements and guidance on collaborative industrial robot operation provided in ISO 10218-1 [27] and ISO 10218-2 [28] ('Safety Requirements for Industrial Robots').

Table 7 List of the task and the dedicated tool identified for disassembling the battery pack considering three robots: one medium payload robot (R1), one medium-high payload (R2), and one IMM. For each tool, the technology chosen is reported as giving motivation

Robot	Task	Tool	Technology	Motivations
Medium payload robot (R1)	unscrewing	impact wrench	pneumatic	cheap; simple; robust; availability of pressurised air; availability of ATEX devices
	sealed part separation	wedge spreader	hydraulic	simple; relatively cheap; high power-to-weight ratio
	cutting wires and hoses	shear	hydraulic	simple; relatively cheap; high power-to-weight ratio
Medium-high payload robot (R2)	part handling	two-fingers gripper for heavy parts	electric	precise control; availability of ATEX devices
	part handling	vacuum gripper for medium weight parts	pneumatic	cheap; simple; robust; availability of pressurised air; compliant with ATEX devices
Industrial Mobile Manipulator (IMM)	part handling	two-fingers gripper for light parts	electric	precise control; availability of ATEX devices

Combining classic safety fences and 3D safety radars was the choice to enable effective human-robot workspace sharing during disassembly operations. The safety fences avoid the operator's access where the access is not supposed to be necessary or dangerous; see Fig. 10. Instead, the 3D safety radar [45], certified as SIL2/PLd, monitors the operator's entrance in the robot working area. The operator's entry into the robot's working area will cause the robot's velocity to slow down to a predefined value or stop the robot, depending on the operator's position and the safety areas configurations. After a predefined timeout, the safety radar can autonomously reset the emergency stop once the operator goes outside the emergency area. The accuracy of the radar is sufficient to detect small operator movements, such as breath movements. The radar can also provide, via a safety field bus (e.g., PROFIsafe), the position and the angle of the closest point of the detected person. Further investigation will evaluate the use of this information for implementing dynamic speed and separation monitoring. The IMM is equipped with a standalone safety system laser and radar for the mobile platform, while the robotic arm is a collaborative robot which applies power and force limiting. It is worth noting that this analysis is insufficient, and a dedicated risk analysis is mandatory. The overall disassembly will also be controlled by infrared cameras monitoring the temperature of the battery pack, being able to raise an alert in case of temperature change prediction of a possible thermal runway with the consequent evacuation of the battery cell. A network of gas sensors will monitor gases emission due to undetected thermal runaways being able to stop the disassembly and evacuate the battery pack from the disassembly cell. The limited use of fences is also thought to easily evacuate the battery pack in case of emergency (e.g., thermal runaway).

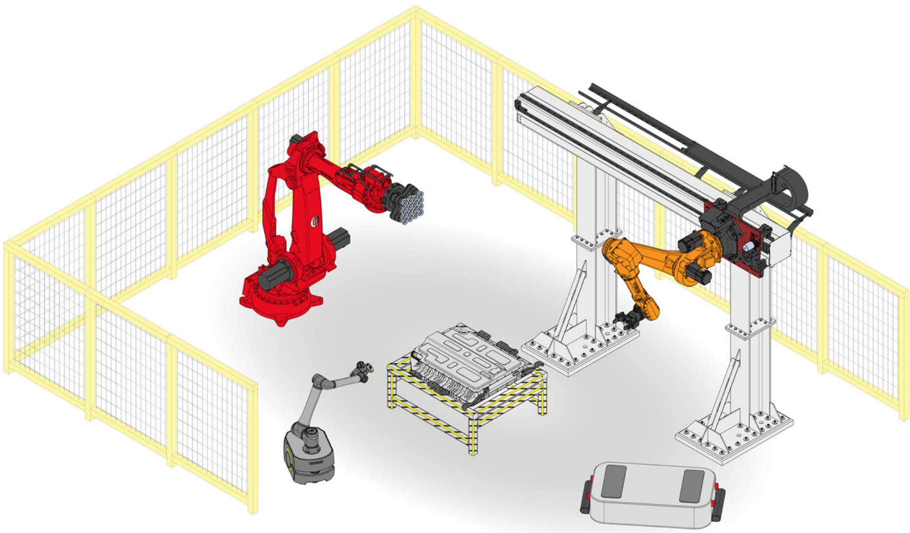


Fig. 10 Possible layout of the safety fences

Conclusion and future works

The massive increment of EVs will produce a consequent increase in battery packs that, within a few years, will reach their EoL. Such a variegated ensemble should be treated appropriately, and the current automation technology needs to be sufficiently developed for the goal. This paper aims to provide guidelines for the design of robotic cells for battery pack disassembly. The work analyses the risk related to disassembly, proposing robot tool design and optimisation according to the current regulation for ATEX zones. The design involves the possibility of a collaborative disassembly considering a semi-automatic disassembly where the operator acts on complex and hardly automatable tasks. Despite the specific use case, the method and the approach are general and easily applicable to various battery packs. The disassembly is thought to preserve the parts' integrity for further reuse and remanufacturing.

Future works will continue to improve the disassembly cell proving the solution on the different battery packs. Trucks and buses' battery packs will also be evaluated because of their size and the number of modules that can further justify automation and robotics during the disassembly.

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Availability of data and material Not applicable.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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