Semi-Autonomous Robotic System for efficient recycling of Lithium-Ion Batteries

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***Abstract*—The increasing popularity of electric vehicles is leading to a massive increase in the use of lithium-ion batteries (LIBs), majority of which will reach their end-of-life in the next decade. Current recycling methods employed to recover valuable materials from end-of-life battery systems involve shredding of individual cells, followed by the extraction of materials through chemical or metallurgical processes. However, this approach often leads to a reduction in the overall yield of valuable materials, and wastage of other auxiliary components. The expected environmental impact of end-of-life LIBs necessitates sustainable recycling solutions. This paper introduces a semi-autonomous robotic system for efficient recycling of LIBs, showcasing a successful collaboration between human, robot, and a disassembly mechanism. The proposed system leverages human skills in removing fragile and deformable battery casing, intelligent grasping capabilities of a robotic manipulator in retrieving individual cells from the battery and the reliability of a disassembly mechanism in extracting the electrode stack from individual cells. By eliminating risks associated with manual recycling and the wastage associated with conventional shredding, the proposed system allows for direct recycling and reuse of LIB components.**

***Index Terms*—lithium-ion batteries, robotics, recycling, circular economy, semi-autonomous disassembly.**

I. Introduction

Climate change poses a significant threat to both our environment and humanity, with transportation being a major contributor to greenhouse gas emissions [1], [2]. To mitigate this, numerous countries globally are advocating for the adoption of electric vehicles (EVs) over traditional vehicles that rely on internal combustion engines. However, these electric vehicles require substantial battery systems to store energy. With the size and weight of these batteries directly affecting the vehicle's range, a key factor in their competitiveness, vehicle manufacturers are trying to include larger, higher capacity battery packs in their upcoming EV models. The preferred choice for energy storage in these vehicles is often Lithium-ion batteries (LIBs). This is primarily because LIBs have higher volumetric and gravimetric energy density, longevity, low maintenance requirements, and high-current capacity. These features enable LIBs to satisfy user demands for EVs with higher speed, torque, and range [3].

In the coming decades, the demand for EVs is expected to further increase; resulting in exponential growth for the lithium-ion market [2]. The demand for LIBs is projected to surge, with an estimated annual growth rate of about 27 percent. A projected 23 million EV cars sold globally in 2030 might result in 5,750,000 tonnes of retired batteries by 2040, assuming a battery life of 10 years and a battery pack weight of 250 kg [4]. This growing demand brings up the substantial concern regarding increasing number of end-of-life LIBs as the production and recycling rates differ significantly [5]. As of today, only a small percentage of LIBs are recycled at the end of their lives, leading to a product life cycle where, the vast majority ends up in landfills, as shown in Figure 1. Addressing the current gap between recycling and production of LIBs is important from an economic and environmental standpoint.

A. *Recycling of LIBs: Economic impact*

In recent years, circular economy has gained pace as a greener solution to raw material production. The core principles of a circular economic approach are: (1) Eliminate waste and pollution, (2) Use products and materials for a more extended period, and (3) Re-generate natural ecosystems. Recycling facilitates internal material movements and plays a critical role in the circular economy (CE) [6]–[9].

In the context of LIBs, recycling and reuse allows for the constituent materials to be used for a longer period and act as a viable option for restoring LIB chemicals into the economic cycle and minimizing reliance on primary raw materials [6]–[12]. As shown in Figure 1, efficient recycling techniques would allow us to invert the end-of-life pyramid for LIBs, leading to better circularity in the use of raw materials. We can not only reduce economic and environmental problems by closing the loop through proper recycling, but we can also create a more sustainable and resource-efficient approach to LIB production and consumption.

B. *Recycling of LIBs: Environmental impact*

Existing recycling techniques largely focus on removing economically useful minerals with direct economic value such as gold, copper, iron, and aluminum, resulting in the active material, especially Lithium oxide, left behind as waste. Some of these recycling techniques also include complete disposal of LIBs or the active materials present in LIBs in the form of landfills [13]–[15]. These techniques contain risks of fire, and explosion, as well as leaching after disposal which can

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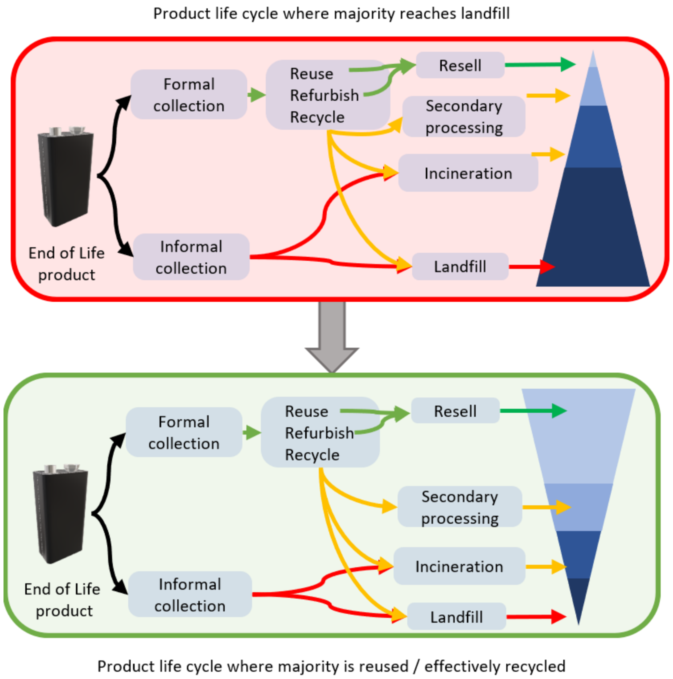

Fig. 1. Achieving circularity in LIB recycling by inverting the end-of-life pyramid

release hazardous pollutants in the form of vapors, gases, metal nano oxides and other toxic products from the electrolyte. These pollutants can be released into soil, water, and air, posing a direct threat to animal and plant species at all trophic levels, as well as a risk to human health. [15]. In addition to addressing the issues of LIB disposal, it is also critical to acknowledge the enormous environmental impact of mineral extraction and smelting operations involved in making new LIB modules. These processes can exacerbate soil erosion and dust phenomenon, aggravating environmental concerns.

The above environmental and economic concerns will make effective large-scale recycling of LIBs a necessity in the coming decades. To address the same, this paper presents a semi-autonomous approach towards efficient recycling of LIBs. The rest of the paper is organised as follows; Section 2 provides an overview of LIB design and existing autonomous, semi-autonomous and manual LIB recycling techniques. Section 3 presents the overall layout of the Semi-Autonomous disassembly. Section 4 discusses the experimental validation using the proposed system on a mock battery. Section 5 concludes the paper with suggestions for future research directions.

II. Literature Review

The following section provides a review of the commonly used LIB designs. The section also provides a review of existing disassembly techniques for LIBs aimed at recycling and reuse of battery material. This review will motivate the need for the proposed semi-autonomous robotic disassembly of LIBs.

A. Review of LIB design

Lithium-ion batteries, particularly the type used in EVs, are structured hierarchically in a ”cell-module-pack” configuration. Because of the high-power requirements of EVs, a large number of battery cells, ranging from dozens to thousands, are required. These cells serve as the base of the battery and must have a high capacity per unit volume in order to optimize performance within the confines of a vehicle's available area. Furthermore, they must have long cycle life and be able to survive the mechanical shocks, vibration, and temperature fluctuations encountered while driving.

To meet the above performance requirements, multiple cells are built into modules within protective frames. The final battery pack will consist of multiple modules, a Battery Management System (BMS), and a cooling device, in addition to the power electronics components and the mechanical structure itself. The BMS is responsible for voltage and current regulation during charging and discharging cycles. The cooling system is responsible for maintaining the temperature of the overall system within limits during operation.

Each individual cell consists of four essential components, namely cathode, anode, electrolyte, and separator.The cells themselves come in three primary form factors: cylindrical, prismatic, and pouch cells [16]. Each of these form factors has its unique advantages and disadvantages, and their selection is primarily driven by specific application requirements.

Among the above designs, currently the pouch and the prismatic cells have higher growth rates in the global market [17]. These battery types offer superior heat management capabilities compared to cylindrical batteries, which can impact overall performance. Pouch cells employ a unique approach where the cells are sealed in a flexible foil container instead of a solid enclosure. Recent pouch cell designs employ a Z-folded stacking, as shown in Figure 5 (a). The Z-stack structure consists of alternating layers of positive and negative electrodes, separated by a separator material, which allows improved energy density and better space utilization within battery modules.

Existing literature consistently highlights the potential of pouch cell batteries for future applications, emphasizing their versatility, energy efficiency, and compatibility with emerging technologies. As such, the proposed semi-autonomous robotic disassembly approach would be designed for and validated on pouch cell batteries with Z-folded stacking.

B. Review of LIB recycling

Among the existing LIB recycling strategies, direct manual disassembly and recycling is the most widely used, especially in developing nations. It involves manual removal of cathode or anode material from the electrode for reconditioning and re-use in a remanufactured LIB. Direct manual disassembly involves high risk, especially in cases where residual charge left in the battery could lead to electrical shocks, leakage of harmful chemicals, explosion and fire, during the disassembly process. In order to prevent this, ceramic blades are recommended for cutting open of individual cells to prevent accidental short

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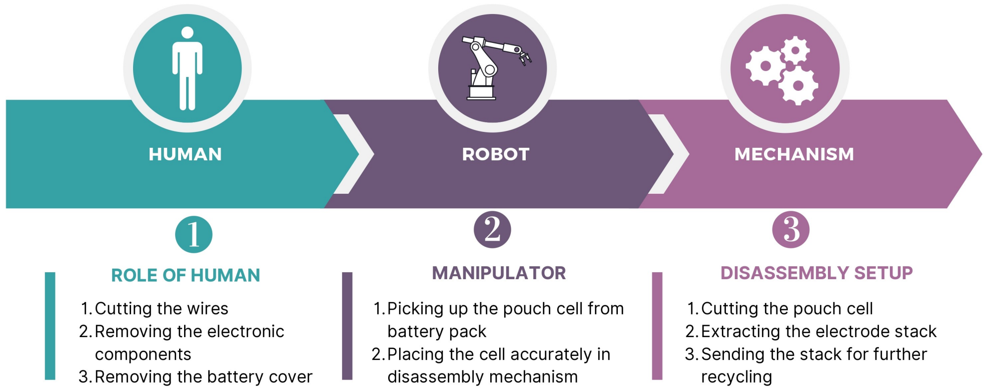

Fig. 2. Semi-autonomous battery disassembly process flow

circuits. It is also recommended to perform manual disassembly while keeping the individual cells inside a glove chamber that maintains an inert atmosphere.

The pouch and separator materials used in the battery cells have lower economic worth when compared to other battery cell components. As such, traditional manual recycling processes do not prioritize the retrieval of these materials [18]. Manual disassembly approaches are also not scalable for handling large volumes of end-of-life LIBs, anticipated in the coming decades [19].

In addition to direct manual disassembling, other major methods used to recycle lithium-ion batteries are pyrometallurgy, and hydrometallurgical treatment. Pyrometallurgy involves melting batteries in a high-temperature furnace to convert metal oxides into a Co, Cu, Fe, and Ni alloy [20]. This method is adaptable and can handle unsorted feedstock and batteries mixed with other waste. Pyrometallurgy, while preferable due to its simplicity and efficient processing, does not allow for recovery of electrolytes, plastics, or other components while also leaving a negative impact on the environment.

Hydrometallurgical operations on the other hand, typically starts with battery shredding and black mass separation, the solid residue that remains after the extraction of valuable metals from spent lithium-ion batteries. Aqueous solutions are then used to leach desired metals from cathode materials in LIBs [20].While shredding results in size reduction and passivation of reactive components, it also yields lower purity products and thereby decreasing process economics [21]. It has been shown that the cost saving using shredded material was generally less than 20%, whereas disassembly could potentially result in cost savings in the range of 40% to 80% depending on purity [21].

Among the three recycling strategies, direct manual recycling stands out for its process simplicity, minimal environmental impact, and profitability among the three [22]. But it suffers from the disadvantages and limitations, as mentioned earlier, making it expensive, dangerous, and wasteful.

III. Design of Semi-Autonomous Disassembly System

Based on the detailed literature review, there is an immediate need for the development of a scalable, efficient, and economical approach towards LIB disassembly and recycling. With the majority being recycled manually, there is high cost, primarily driven by labour expenses and the safety considerations necessary to prevent electrical and chemical hazards. Additionally, many of the disassembly steps involved in battery recycling are repetitive and time-consuming. The above challenges make LIB recycling an excellent case for automation, which would also make it economically viable and scalable to handle the increasing demand for batteries.

However, it is important to acknowledge that while automation excels in some aspects, it lacks the inherent flexibility, and adaptability possessed by humans. Traditional factory automation relies on organised environments in which robots execute pre-programmed operations on precisely known items in predetermined configurations. In contrast, the presence of soft, fragile, and flexible components in batteries such as soldered wires, adhesive seals, and insulating covers makes it difficult to develop a fully automated system for addressing the disassembly requirements. Moreover, lack of standardisation in battery pack, module, or cell design in the automotive industry also introduces variations in the disassembly process, making it difficult to address through automation [23].

Wegener et al. [24] have recommended a hybrid approach involving both human worker and robotic automation for EV battery disassembly. The automated system can handle repetitive and mundane tasks, freeing up human workers to focus on more complex tasks. A human worker could also provide the necessary oversight, decision-making, and problem-solving skills that automation may lack. This would result in an efficient and scalable approach towards battery recycling while minimizing the safety risk to human employees. While the installation cost of such a system could be high, the running cost over large volumes would be lower, making recycling economically viable [24], [25].

Keeping the requirements and inferences from existing

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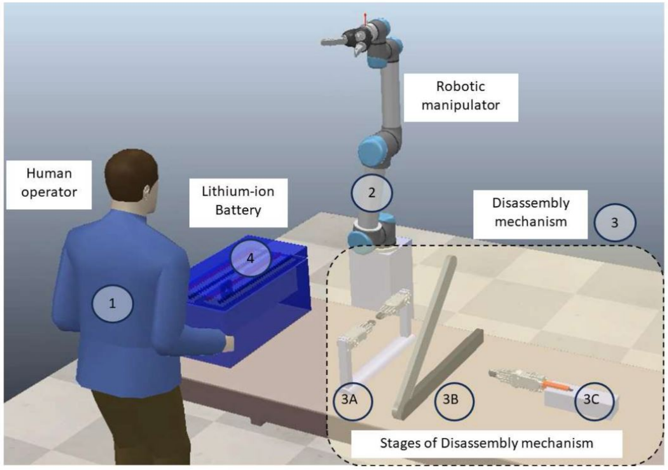

Fig. 3. Overall layout of semi-autonomous disassembly system, showing the four sub-entities involved: human operator (1), robotic manipulator (2), a disassembly mechanism (3), and the LIB to be disassembled (4)

literature in mind, we propose a semi-autonomous robotic approach towards the disassembly of LIBs. The proposed approach involves a human operator, a robotic arm, hereafter referred to as a manipulator, and a disassembly mechanism, working together to extract an electrode stack from an LIB pack. The proposed workflow is summarized in Figure 2. The human operator is required to remove the flexible components, while addressing the variations in the battery design. The robotic system would be used for performing the repetitive tasks, such as removing individual cells from the module. A disassembly mechanism, specifically designed for the battery type, will be used for tasks such as cutting open the individual cells to remove the electrode stack. Since the disassembly mechanism could be placed in an inert atmosphere environment such as a glove chamber, it minimises the risk associated with cell opening.

The proposed approach is customizable for different battery designs and scalable to handle the increasing volume of LIBs, while ensuring safety of the human worker involved in the process. The following subsections will discuss the semi-autonomous battery disassembly process in detail, as well as present the design of an equivalent battery on which the proposed approach would be validated.

A. Semi-autonomous battery disassembly process

The overall layout of the semi-autonomous disassembly system is presented in Figure 3 and the steps involved in the disassembly process are detailed in Figure 4. The human operator is required to perform operations that require dexterity and cannot be accomplished by the robotic manipulator. This involves removing the top cover of the LIB, unscrewing and/or cutting open any seals on the battery as well as de-soldering any wires that secure the individual cells to the battery management system and the output terminals, as shown in Figure 4 a) and b).

The robotic manipulator and the disassembly mechanism together perform operations that are hazardous for the human operator. Repeated tasks such as picking up the individual pouch cells from within the LIB and accurately delivering them to the disassembly mechanism will be carried out by the robotic manipulator, as shown in Figure 4 c), d) and e). Further processing of individual cells to remove the electrode stack for recycling will be handled by the dedicated disassembly mechanism. The mechanism is divided into three distinct stages. The first stage performs accurate positioning and gripping of the pouch cell, as shown in Figure 4 f). The second stage focuses on cutting open the pouch cell to expose the electrode stack, as shown in Figure 4 g). The third stage allows for retrieving the electrode stack from each pouch cell as shown in Figure 4 h) which can then be sent for further electrochemical processing.

B. Design of equivalent battery

The wide variety of requirements for LIBs, even within the EV domain, results in the need for customization in terms of size, capacity, voltage, and other specifications. As mentioned before, this leads to lack of standardization in LIB pack, module, or cell design, making it difficult to choose a particular battery model for validating the proposed semi-autonomous disassembly process. In addition, Lithium batteries contain toxic chemicals, which can pose a risk to human health if not handled properly. As such, testing and validating a novel disassembly approach on a real LIB pack poses health and safety risk to the researchers involved.

Taking the above facts into consideration, an equivalent LIB model was designed and fabricated to test, tune, and validate the proposed semi-autonomous disassembly technique. The pouch cells in the equivalent battery were made using materials that closely mimic the properties of real cells, while excluding the active materials like lithium-ion, due to its poisonous nature. Aluminium foil was used as cathode and copper foil as anode. Porous polypropylene sheets were used to replicate separator material.

The outer cover of an LIB pouch cell typically consists of a composite sheet made of polymer and aluminium. A similar pouch made of composite material and form factor was used in the equivalent battery. Similar to the LIB cells, a Z-stacking design was used to pack the anode, cathode and separator into the pouch cell. The detailed CAD design of the equivalent pouch cell is shown in Figure 5 a), and the prototype is shown in Figure 5 b) and c). Ten pouch cells were stacked together to create a module. Finally, two modules were put together to create the equivalent battery pack.

The exterior of the battery was built using acrylic sheets held in place with 3D printed corner pieces. Figure 6 a) shows the CAD model annotating different parts of the equivalent battery. Figure 6 b) shows the integrated prototype.

IV. Experimental Validation

The following section presents experimental validation of the proposed semi-autonomous disassembly approach on an

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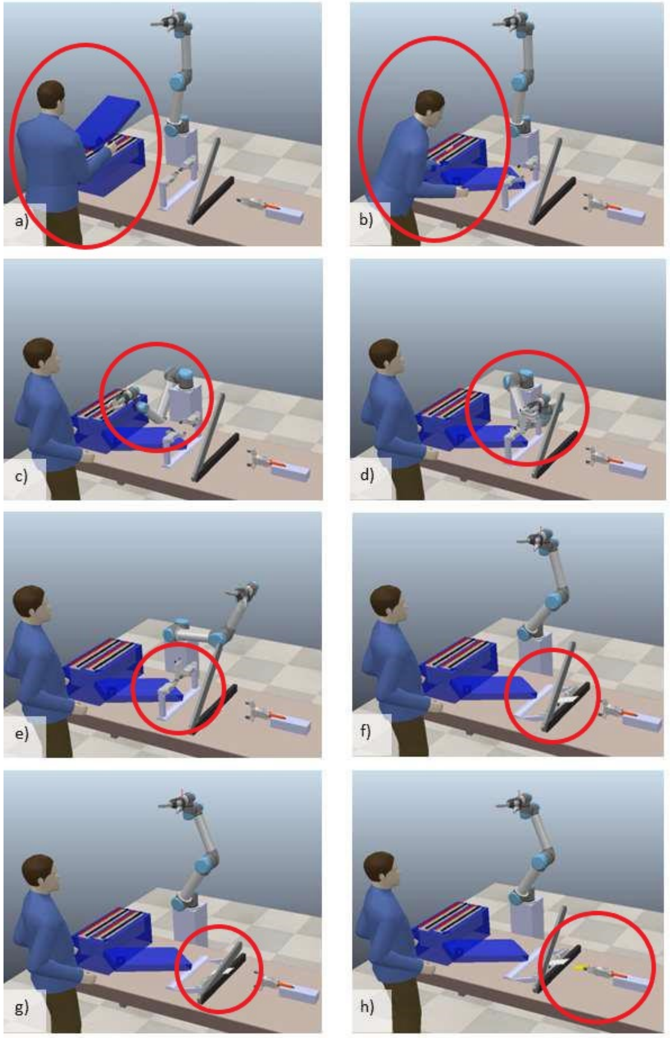

Fig. 4. Steps involved in semi-autonomous LIB disassembly

equivalent battery. A detailed assessment of the proposed approach for large scale LIB recycling is also presented.

A. Experimental setup

Figure 7, and Figure 8 shows the experimental setup consisting of the equivalent battery, UR5e robotic manipulator and the disassembly mechanism. Figure 9 shows the steps involved in the disassembly process. To begin the disassembly process, a human worker is required to remove the top cover from the battery. The equivalent battery was provided with an AprilTag [26]. A calibrated camera was mounted overhead, which allowed for estimating the position and orientation of the equivalent battery. The position of the pouch cells within the battery could then be estimated based on the battery design. This information was used to plan a feasible path for the UR5e manipulator from its starting configuration as shown in Figure 7 a) to the goal configuration as shown in Figure 9 a), where it can precisely grasp the pouch cell from the battery module.

The manipulator is being externally controlled through the Robot Operating System (ROS) [27]. Autonomous path

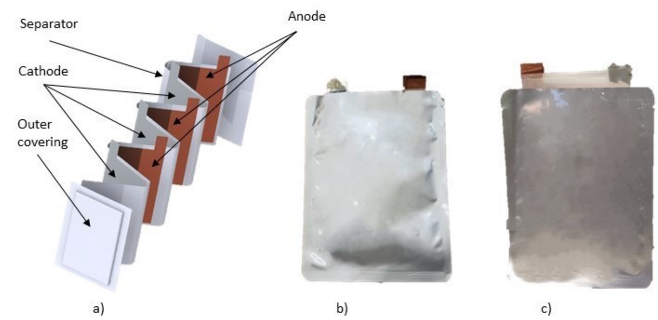

Fig. 5. Equivalent pouch cell a) Design with exploded view, b) Physical prototype, c) Prototype with inner stack exposed

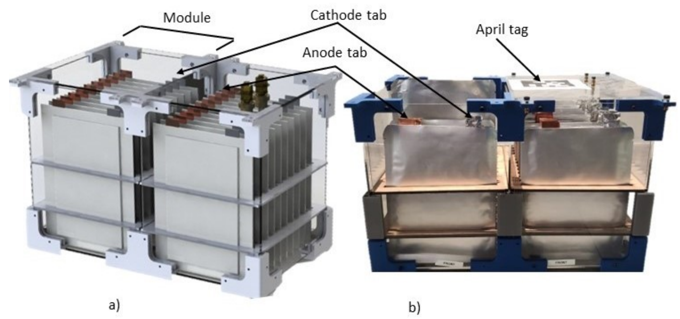

Fig. 6. Equivalent battery a) Design b) Physical prototype

planning with obstacle avoidance and grasp planning was implemented for the UR5e manipulator using MoveIt [28], a ROS-compatible motion planning framework. After successfully grasping the pouch cell, intelligent path planning is employed through MoveIt, with the starting configuration as shown in 9a) to the goal configuration as shown in 9b). At this goal configuration, the UR5e manipulator can precisely deliver the pouch cell to the disassembly mechanism. Rapidly-exploring Random Trees connect (RRT-connect) [29] algorithm, a sampling-based motion planning technique from OMPL, was used to generate an efficient and collision-free trajectory for the UR5e manipulator. Figure 8 shows the detailed layout of the disassembly mechanism, along with the components.

Stage 1 consist of a swivel arm with two grippers, all controlled by MG995 metal gear servo motors. An ultrasonic sensor is provided on the arm allowing it to detect the presence of the pouch cell, as it is being delivered by the robotic manipulator, to automatically trigger closing of the grippers, as shown in Figure 9 b) and c). Once the grippers are closed, the arm is made to swivel with respect to the base, allowing it to precisely place the pouch cell on the cutting mechanism (Stage 2), as shown in Figure 9 d).

Stage 2 employs an industrial cutter operated by a DC motor with limit switches on both extreme positions. The default position of cutter is open, as shown in Figure 9 d). Once the pouch cell is placed on the cutter the, the motor is actuated to perform a precise cut on the pouch cell, after which the cutter returns to open position, as shown in Figure 9 e), and f).

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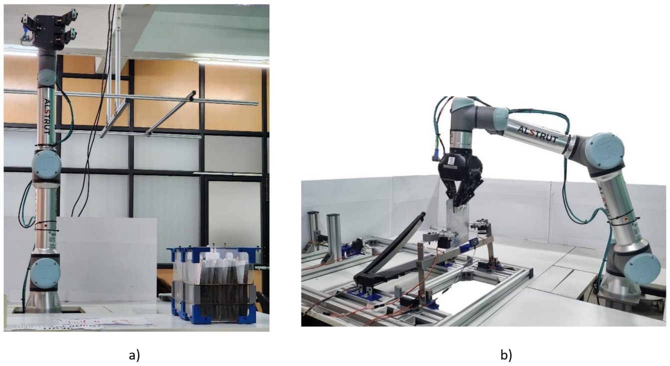

Fig. 7. Robotic manipulator used for disassembly a)Start configuration with battery, b) Pouch cell delivered to disassembly mechanism

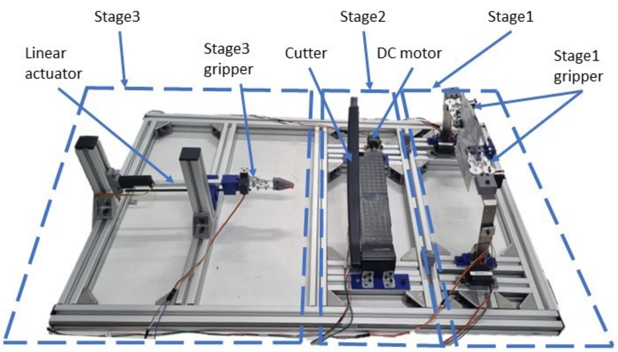

Fig. 8. Layout of the disassembly mechanism

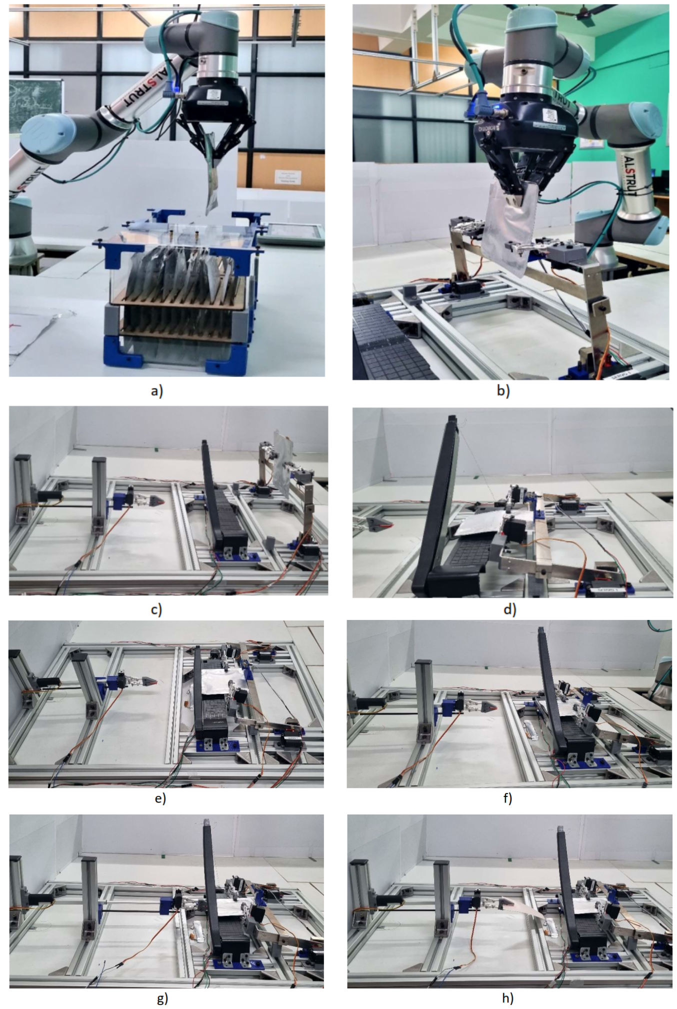

Fig. 9. Steps involved in the disassembly process a) The manipulator picks up a pouch cell from the battery b) Placing the pouch cell on stage 1 of the mechanism c) Stage 1 grippers closed d) Pouch cell is placed in position for Stage 2 e) Pouch cell is cut open f) Cutter goes back to open position g) Stage 3 grasps the electrode stack h) Electrode stack extracted

Stage 3 uses a linear actuator with a gripper at the end to pinch and extract the electrode stack from the pouch cell, as shown in Figure 9 g), and h). The gripper uses MG995 metal gear servo motor. The control of the individual stages based on timing and sensor detection (ultrasonic sensor and limit switches) was performed using an Arduino micro-controller. The base frame of the mechanism was built using 40x40 aluminium extrusion.

Multiple trials of battery disassembly were performed, and the average time taken for the complete disassembly operation, starting with the human operator removing the battery cover to the disassembly mechanism extracting the electrode stack, was four minutes. It should be noted that the above timing depends on the speed of the manipulator, different stages of the mechanism and the human operator. While this was the best possible time achievable by the proof of concept system, it could be improved significantly through the use of better actuators in the disassembly mechanism, along with a trained human worker.

B. Comprehensive assessment of the proposed system

Environmental concerns stemming from the current approach to LIB recycling are evident, with less than 40% of total battery materials being effectively recycled under existing material flow schemes, leading to economic losses and environmental damage due to the unrecovered valuable materials and their subsequent disposal [21]. As of today, the world lacks sufficient LIB recycling infrastructure, with only a few full-scale recycling facilities in operation.

The concept of direct manual recycling in the context of LIBs holds significant promise from an environmental perspective. It aligns well with the principles of sustainability and circular economy, maximizing resource utilization, while minimizing the environmental footprint. However, direct manual recycling does face a key challenge - the demand for substantial man-power, with the associated safety hazards. This labour-intensive aspect renders it economically infeasible for widespread adoption [30]. The proposed approach involves pairing a human worker with a robotic system and a disassembly mechanism, while still maintaining the advantages of direct manual recycling, making it more economical and scalable.

While the proof-of-concept system presented in this work employs a disassembly mechanism tailor made to suit a specific pouch cells design, it could be extended to accommodate

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different types of pouch cell variants. This could also be addressed if the battery industry moves towards a standardized cell design.

V. Conclusion

The existing scenario for LIB disposal lacks universal guidelines. The lack of defined processes raises the potential of faulty or irresponsible processing and disposal, resulting in soil, water, and air contamination. Direct recycling of lithium-ion batteries (LIB) surpasses traditional approaches in terms of efficiency and sustainability. To this extent, we proposed a semi-autonomous robotic system towards efficient recycling of LIBs, showcasing a successful collaboration between human worker, robotic manipulator, and a disassembly mechanism.

The proposed system enables the safe removal of pouch cells from the battery pack and facilitates the subsequent extraction of the electrode stack from the pouch cell. The proposed approach could provide significant improvements in the quality of the recycled material as compared to the traditional shredding strategy. Moreover, our approach is adaptable to different battery designs and scalable to handle the increasing volume of LIBs reaching the end-of-life stage.

VI. Acknowledgments

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VII. Patent

The semi-autonomous battery disassembly system presented in this paper is covered by a provisional patent filed with the Indian Patent Office. Patent application number: TEMP/E-1/60202/2023-

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