Autonomous Battery Sorting and Disassembly: Addressing Critical Raw Material Scarcity in Modern Manufacturing

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Abstract

Critical material shortages and rising safety risks in recycling facilities underscore the need for improved Li-ion battery recycling methods. This project develops two automated technologies to increase the safety, efficiency, and economic viability of battery recovery. First, a robotic system for disassembling HEV, PHEV, and BEV battery packs is being designed for pack-to-module teardown. Second, an AI-enabled sorting system is being developed with high-speed vision and modular gantry pick-and-place mechanisms to classify and separate consumer batteries by chemistry. Together, these demonstrations will provide data for techno-economic analysis and establish scalable pathways for safer handling, higher-purity black mass, and strengthened domestic supply of critical battery materials.

Introduction and Motivation

The shortage of critical raw materials for manufacturing consumer and industrial-grade batteries threatens continued growth of modern products. As these raw materials, lithium, nickel, cobalt, graphite, and manganese, are available in limited supply within the USA, developing a cost-effective recycling process is essential to ensure long-term sustainability and to reduce dependence on limited natural resources. Current battery recycling processes are largely manual or semi-automated. These methods are costly and result in significant raw material waste. Automation of the recycling process can improve purity and value of the resulting material.

This project addresses critical challenges in battery recycling, both in consumer batteries and large-format electric vehicle (EV) battery packs. Unlike efforts such as the ReLiB Project [1] or the Battery Recycling and Automating Circular Economies (BRACE) Lab at Oak Ridge National Laboratory [2], this project is not intended to conduct basic research on individual battery recycling processes. Instead, the goal of this project is to test and demonstrate emerging, viable technologies for realistic industry applications. Industrial partners from the recycling industry and automotive OEMs are providing insight and sample materials for both tracks. In the first task, consumer batteries are received within the stream of mixed recyclables. AI-based software provided by an industrial partner will be used to identify and classify batteries by chemistry. An automated sorting system will use the battery classification to collect the batteries by chemistry for shredding into high purity black mass. While the demonstration planned is targeted at sorting a variable mix of products, the demonstration is limited to a subset of the population of battery types. Future analysis will include potential enhancements needed to deal with expected product diversity in a future commercial system implementation. In the second task, efficient autonomous methods are being developed to disassemble Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV), and Battery Electric Vehicle (BEV) battery packs into modules and other sorted recyclable components that can be shredded into high purity black mass or further disassembled. As much as is practical, disassembly methods will be commonized between the selected battery packs to enable flexibility in accepting future battery packs. This paper will describe the current progress of the work in both tracks. As the work is ongoing at the time of publication, technical details and results are not yet available.

The project team is composed of the lead organization, engineering and demonstration partners, recycling industry partners, and automotive industry partners. The lead organization is Centrepolis Accelerator, a hardtech incubator within Lawrence Technological University (LTU) offering support to hardtech startups and small to medium-sized manufacturers through access to product development services and tailored funding solutions. The engineering and demonstration partners are LTU Robotics Engineering faculty and students, Automated Industrial Robotics, UHV Technologies, Inc., and Munro & Associates, LLC. The recycling industry partners are GLR Advanced Recycling, Goodwill Industries of West Michigan, Inc., PADNOS, and Planet Environmental Solutions, LLC. The automotive industry partners are Ford Motor Company and Stellantis NA.

Review of Related Work

Trends in EV Battery Pack Recycling

As the number of EVs sold grows, as shown in Figure 1, the number of EV battery packs available for recycling is also rapidly growing due to recalls, collisions, and usage. A summary of HEV, PHEV, and BEV manufacturers within the US market is shown in Table 1. As of late 2025, lithium iron phosphate (LFP) battery packs remain extremely rare in the US outside of a few Tesla standard-range trims (built with imported CATL/ BYD cells). More than 90% of BEV packs are nickel manganese cobalt (NMC) or nickel cobalt aluminum (NCA). Due to lower costs, growth of LFP and LMFP are projected to expand further beyond 2025 [1]. All other major US-sold BEVs use nickel-rich NMC or NCA packs for higher energy density and longer range. Economics of recycling of LFP batteries will be even a larger challenge due to reduced value in raw materials.

End-of-life EV battery packs can be recycled into the black mass, refurbished for additional use in EVs, or remanufactured into second-life batteries (SLB) for stationary applications like energy storage. Kamath et al. has shown that the selling price of SLBs depends on the state of health of the battery at the end-of-first-life, the cost of a new battery, and warranties used on the SLBs [3]. Similarly, Groenewald et al. determined a feasibility test for remanufacturing of used EV battery packs [4]. For EV battery packs that are not economical to reuse as SLB or remanufacture, recycling remains viable for material recovery.

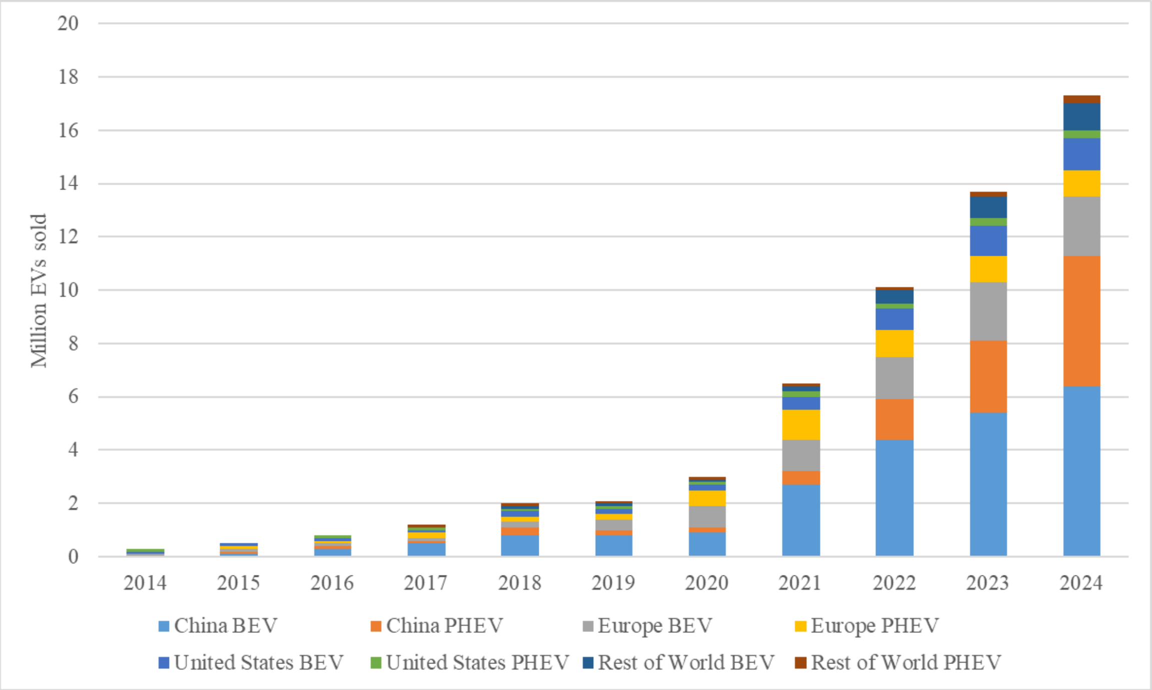


Figure 1. Global electric car sales, 2014-2024 [2]

Table 1: Summary of EV Manufacturers in the US Market (as of November 2025)

Category	Dominant Manufacturers	Battery Chemistry
HEV	Toyota/Lexus, Honda/Acura, Hyundai/Kia, Ford	Almost exclusively NMC (some older NiMH)
PHEV	Toyota, Jeep/Chrysler, Ford, Mitsubishi, BMW/Mini	NMC/NCA
BEV	Tesla, GM (Chevy/GMC/Cadillac), Ford, Rivian, Lucid, Hyundai/Kia, VW/Audi, Mercedes, BMW	NMC/NCA (>90%)
	Tesla only (standard-range Model 3/Y)	LFP (<10%)

Recycling of Li-ion batteries can be split into pyrometallurgical, hydrometallurgical, and physical processes. Thompson analyzed different hydrometallurgical recycling processes (pre-treatment, dissolution process, recovery process) from the literature. While shredding the packs is mechanically simple and requires less labor, it is more chemically complicated and those processes that started with disassembly instead of shredding provided significantly higher profit [5]. Leon and Miller showed that labor costs for manual disassembly made mechanical pre-treatment a less cost-effective strategy than thermal pre-treatment [6]. For a single design of battery pack, Hathaway et al. identified that 81% of pack-to-module disassembly steps could be fully automated or semi-automated [7]. Lander et al. examined the disassembly time and cost for manual, semi-automated, and fully automated disassembly of five battery packs from different manufacturers and determined that a fully automated process could reduce the disassembly cost by 97% [8].

Full or partial automation of EV battery pack disassembly is an area of active research, including telerobotics [9], human-robotic collaboration [10], AI [12], machine learning [13], and more. In addition to individual components, some complete systems have been developed. Oak Ridge National Labs demonstrated a robotic battery disassembly system [14]. Comau's Flex-BD cell is capable of removing the battery pack cover, unscrewing modules, and removing modules [15]. MTC has introduced a battery teardown facility sized to fit in a shipping container [16].

Trends in Consumer Battery Sorting

The increase in consumer electronics has resulted in an increase in Li-ion batteries within the waste stream, including at material recovery facilities (MRFs) and landfills. Extraction of these batteries serves both to recover critical materials and to lower the risk of fires due to Li-ion batteries. The US Environmental Protection Agency has recorded an increase in fires at waste management facilities, as shown in Figure 2, with 89% definitively caused by Li-ion batteries and the rest likely caused by Li-ion batteries [17]. These fires have resulted in injuries, service disruptions, and monetary costs.

Recyclers, like project partner PADNOS, often use manual labor for sorting batteries from the waste stream. However, automated methods are becoming more capable at identifying and separating specific items. Sortera, a spinoff of project partner UHV, uses AI to analyze and sort each 1 inch to 4 inch piece of shredded automotive parts [18]. Glacier uses computer vision to identify specific recyclables and sort them with a robot and has deployed to several MRFs [19]. ZenRobotics has deployed AI-powered robotic scrap metal sorting systems [20]. Fully automated sorting methods remain an active research topic including construction and demolition waste streams [21] and plastics in municipal waste [22]. General waste sorting tends to rely on computer vision including the YOLO model.

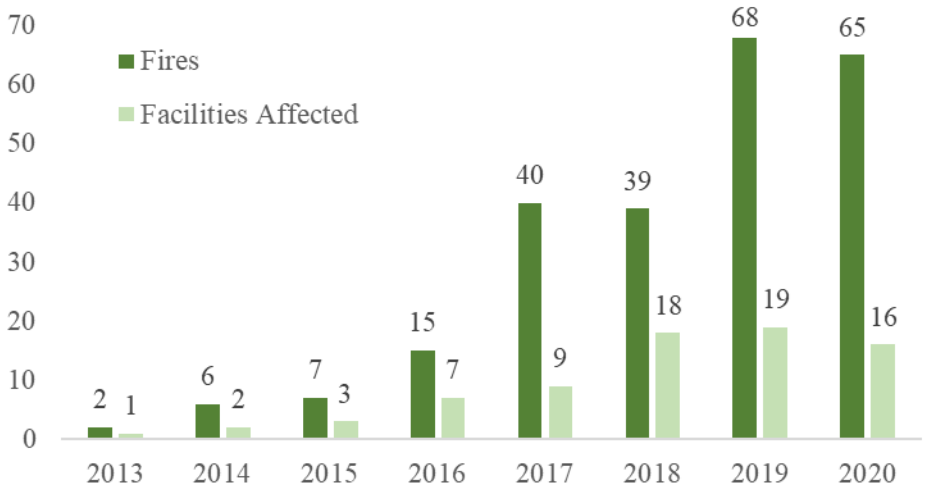


Figure 2. Increase in fires at US waste management facilities with most (89%) caused by Li-ion batteries and the rest likely caused by Li-ion batteries [17]

Technology Approach & Discussion

This project focuses on developing two distinct yet complementary technology demonstrations leveraging the use of automated robotics and AI pattern recognition software with vision systems to improve disassembly of EV battery packs and downstream identification and sorting of different battery chemistries. Recovery of end of life battery minerals will 1) provide profitable margins for recycling firms; 2) to avoid fires in material recovery facilities; 3) avoid waste in our landfills; and 4) provide a steady stream of battery materials that can be utilized again in battery cell manufacturing plants. Demonstration 1 includes the design, development, testing and demonstration of robotic processes for the automated disassembly of end of life EV battery packs down to the module level. Demonstration 2 focuses on high-volume consumer battery cell sorting using an AI pattern recognition technology. Each demonstration will be discussed in the following sections.

Demo 1: Robotic Disassembly of End of Life Automotive Battery Packs

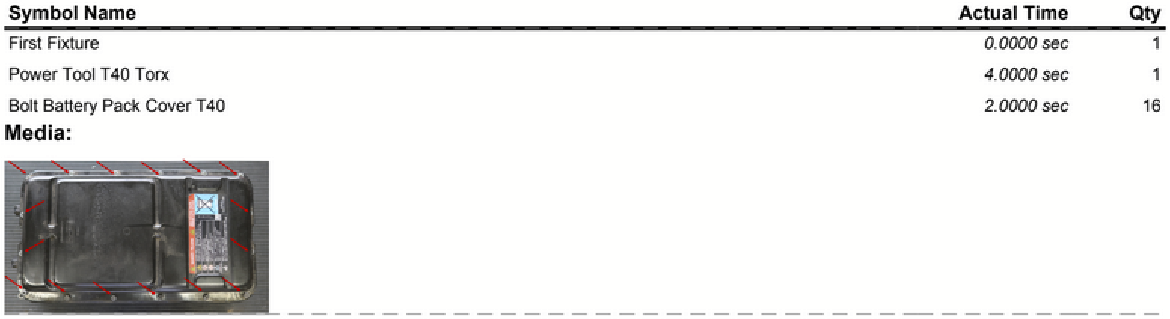
In this demonstration, a robotic disassembly cell for handling end of life automotive battery packs will be designed, constructed, tested, and validated with real battery packs representing a range of sizes and constructions (HEV, PHEV, and BEV). At this stage of the project, battery packs will be dismantled down to the module level with removed components sorted into discrete waste categories for further processing. Disassembly of battery modules to further separate down to cells was not within scope of this project.

Three types of production battery packs were selected and donated by project partners. The HEV battery pack was taken from a Ford Maverick, the PHEV battery pack was taken from a Jeep Wrangler 4xe, and the BEV battery pack was taken from a Fiat 500e. A comparison of packs is provided in Table 2. For each pack considered, 10 samples were made available for the project. Project sponsors provided manual disassembly instructions but did not provide CAD data as that was considered proprietary information.

Table 2. Comparison of considered automotive EV battery packs.

Type of Pack	Vehicle	Capacity	Total Mass	Number of Modules
HEV	Ford Maverick	1.1 kWh	32 kg	2
PHEV	Jeep Wrangler 4xE	17.3 kWh	170 kg	8
BEV	Fiat 500e	24 kWh	272 kg	18

As a first step in development of the automated process, a manual teardown was completed on one sample of each battery pack. The teardown was completed by Munro & Associates. All steps in the teardown process were documented in the Munro Design Profit method, including the tools required and time to complete, with photos to identify specific components or component locations. Photo and video documentation were shared with project partners. A sample step from the disassembly documentation for the HEV pack is shown in Figure 3. During the teardown process, there was discussion on the key decisions necessary for automation. These included the distribution of disassembly steps between automated and manual processes and which disassembly steps could be destructive in nature for the purpose of proper sorting of materials for downstream sorting and processing.



Symbol Name	Actual Time	Qty
First Fixture	*0.0000 sec*	1
Power Tool T40 Torx	*4.0000 sec*	1
Bolt Battery Pack Cover T40	*2.0000 sec*	16

Media:

Figure 3. Sample step from disassembly documentation for HEV battery pack.

Complicating the disassembly planning, the battery packs arrived with a range of voltages. Ensuring either safe discharge of the battery packs or safe handling of charged battery packs was determined to be a critical decision in the demonstration. The team determined that the technical challenge of handling charged modules was going to be difficult to overcome and it was determined that bulk discharge of the battery packs would be done prior to disassembly. A Maroo Power battery discharge unit (MPD-S1000100) was selected for this demonstration. The battery discharge unit is capable of discharging up to four Li-ion batteries up to 1 kV at up to 100 A.

The automated disassembly cell is being designed by Automated Industrial Robotics (AIR). As of the writing on this report, AIR has proposed a cell using battery-pack-specific fixtures with interchangeable end-of-arm tools secured with quick change couplers. A summary of the end-of-arm tools is provided in Table 3. Each battery pack requires a unique sequence of operations, but there are common elements. As an example, a portion of a simplified version of the proposed sequence of operations for the HEV battery pack is provided in Table 4.

Table 3. Summary of proposed end-of-arm tools for automated battery pack disassembly cell

	HEV	**PHEV**	**BEV**
Fastener Removal	X	X	X
Vacuum Cover Removal	X	X	X
Busbar Guillotine		X	X
Wire Harness Nipper	X	X	X
Battery Pack Gripper 1	X		
Battery Pack Gripper 2		X	
Battery Pack Gripper 3			X

Table 4. A portion of a simplified sequence of operations for HEV battery pack

Description	**Manual/Auto**	**EOAT Used**
Operator removes fasteners from cover and places cover to the side	Manual	
Operator completes discharge process	Manual	
Operator reinstalls cover using specific fasteners	Manual	
Battery pack is loaded into automation cell	Manual	
Robot removes fasteners from cover, drops fasteners in bin	Auto	Fastener Removal
Operator changes to vacuum EOAT	Manual	
Robot removes cover and places in bin	Auto	Vacuum Cover Removal
Operator changes to nipper EOAT	Manual	
Robot cuts wire harness, gripper used to place wire harness sections in bin	Auto	Wire Harness Nipper

The immediate next steps of Demo 1 include final approval of the AIR automation proposal, procurement of the robot for the disassembly cell, and purchase of other equipment. LTU Robotics Engineering students will work with AIR staff to help with designing end-of-arm tools. After the automated disassembly cell has been assembled and tested, the remaining battery packs will be disassembled as a final validation of the cell and process. A techno-economic analysis report will be prepared using data from the demonstration.

Demo 2: High-Volume Consumer Battery Sorting

The volume of consumer batteries, particularly lithium batteries, in the waste stream has increased steeply year after year. Waste processors and recycling project partners PADNOS and Goodwill Industries of West Michigan confirm that as their volume of recoverable materials increases, new challenges with safety and cost associated with battery disassembly and sorting have led to challenges in their operations.

PADNOS provided 55-gallon drums of mixed consumer batteries from their recycling operation for use in this project. One drum was manually inventoried to better understand the distribution of battery sizes and chemistries. Figure 4 shows the number and mass of each battery type within the drum and the percentage of total battery mass of each chemistry within the drum. While this is only a single drum from a single recycler, it shows that the largest number of batteries are AA size and alkaline but the largest mass of batteries is Li-ion. Based on the battery distribution from the manual inventory and judgement about the form factors of the batteries within the provided sample, four battery classes were selected for use in this demonstration. The selected battery classes are: 9V (alkaline), laptop (Li-ion), power tool (Li-ion), and packs of cylindrical cells (Li-ion).

The autonomous battery sorting system is composed of several integrated subsystems: the conveyor with speed measurement and control, the vision-based AI classification system, the battery sorting system, and the embedded communication network, as shown in Figure 5. For high throughput, each battery class to be sorted has at least one designated collection system within the battery sorting system. Each subsystem will be briefly described.

Conveyor with Speed Measurement and Control

The conveyor system transports unsorted batteries from the feeder, through the vision-based AI classification system, to the battery sorting system. For the purposes of the demonstration, battery samples are initially fed onto the belt by a small-scale vibratory feeder. The conveyor in the prototype is approximately 1 foot in width and 5 feet in length with a maximum speed of 5 ft/s [1.524 m/s]. Conveyor speed is measured with a 500 PPR rotary encoder (CALT GHW38). The encoder shaft has a spring mounted 300 mm polyurethane disc designed to stay in contact with the conveyor belt at all times. The encoder is monitored with a network interface module and speed is shared over the embedded communication network.

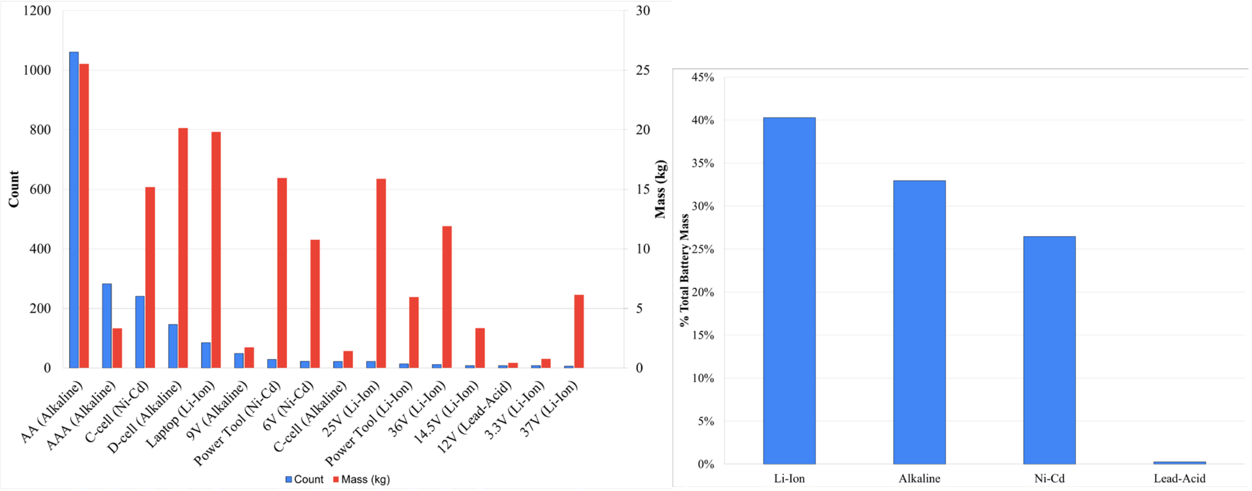


Figure 4. Battery count and mass by type and percentage battery mass by chemistry within PADNOS-provided 55-gallon drum.

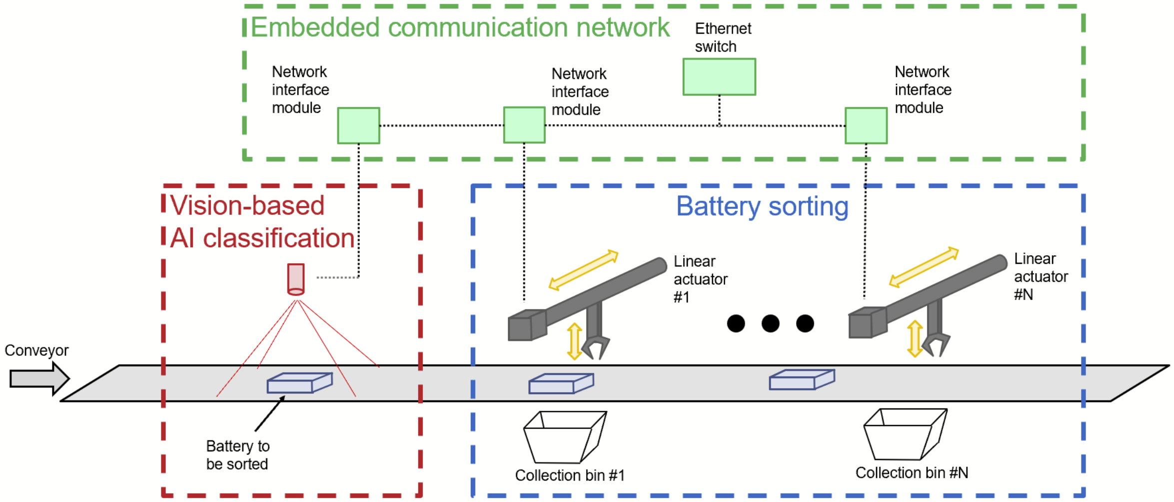


Figure 5. Schematic representation of the autonomous battery sorting system.

Vision-Based AI Classification

The vision-based AI classification system is provided by UHV Technologies, Inc. Battery samples are brought by the conveyor into the camera field of view. Consistent lighting is provided by 8 LED lamps behind a diffuser. The camera (Basler acA40-750uc) captures images at 554 frames per second. A computer running Ubuntu receives the camera images for image processing and AI classification.

Currently, a YOLO (You Only Look Once) model is used to perform object detection and orientation estimation. A YOLO model is a real-time object detection algorithm that divides an image into regions and predicts bounding boxes and class probabilities directly in a single evaluation, enabling fast and efficient detection. Originally developed by Joseph Redmon and colleagues at the University of Washington in 2016 [24], YOLO introduced a unified approach to object detection that replaced multi-stage pipelines with a single end-to-end neural network, making it one of the fastest and most widely adopted detection frameworks [25, 26, 27].

Outside of the deep learning model, UHV provided a custom user interface to integrate with the conveyor system. When the model detects the target object, the UHV-developed conveyor interface provides the object's coordinates within the camera's field of view to the embedded network system, where they are used to calculate the pickup location of the battery. The combination of battery class, pickup location, and orientation is supplied to the rest of the system through the embedded communication network.

Battery Sorting System

The battery sorting system will consist of a set of 2D gantry systems mounted over the conveyor. Each battery class to be sorted will have at least one gantry assigned to it with collection bins on either side of the conveyor. This configuration allows each gantry system to be designed with a gripper or vacuum pickup mechanism that is battery-specific. In addition, battery sorting capability and throughput can be increased as demand for sorting increases. Additional battery classes can be added by retraining the vision system and adding a gantry system. Battery throughput can be increased by adding gantry systems for the most common battery classes without having to dramatically increase the gantry movement speed.

The first prototype gantry system is shown in front and side views in Figure 6. The structural frame is constructed of extruded aluminum links and was designed for ease of use, ease of modification, and high stiffness. Counterweights were added to prevent tipping while in motion. Linear carriage rails were installed to support the horizontal motion system. Future iterations of the structural frame will focus on reduced mass and cost. The battery sorting system includes actuation in both the horizontal and vertical axes. The horizontal axis is powered by a 500 W AC servo motor driving a ball-screw-mounted platform. Integration of the AC servo motor includes a safety relay, line filter, and motor driver. The horizontal axis stroke is designed to allow for the platform to extend past the conveyor edge on both sides, enabling collection of sorted batteries on both sides. Limit switches provide software stops on both ends of the horizontal motion. As of the writing, the vertical axis is still being designed. The expected vertical axis stroke is 6 inches, based on the maximum height of the considered battery classes. A rotary axis between the vertical axis and the gripper may be needed to account for battery orientation.

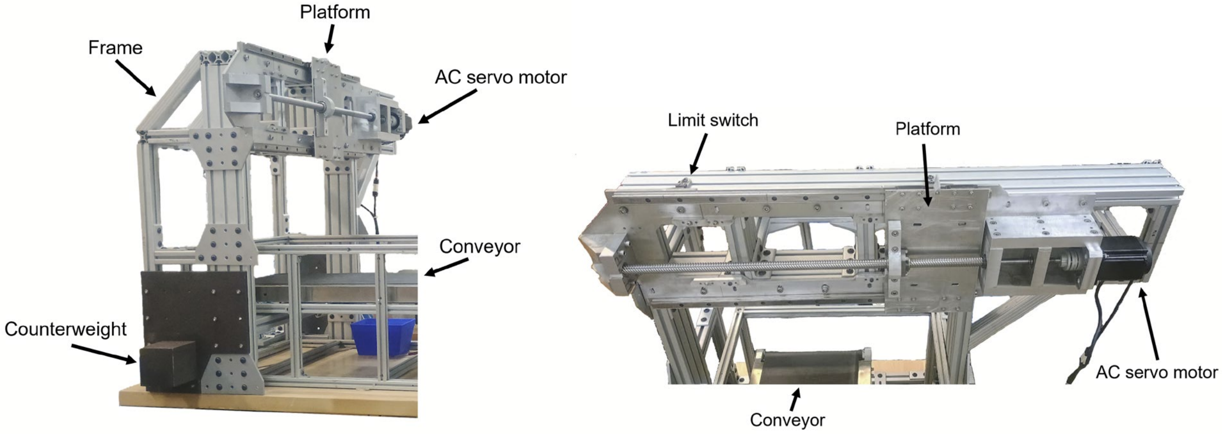


Figure 6. Battery sorting system side and front views showing frame, ball screw, and AC servo motor.

Embedded Communication Network

The embedded communication network ensures all subsystems operate in synchrony. This network consists of Interface Modules, a low-cost, multi-purpose sensing interface, and the Network Hub, which manages and routes all inter-system communication.

The Network Interface Module was custom designed for this application. The custom printed circuit board is built around the WT32-ETH01, a dual-core ESP32-based microprocessor that integrates a wired Ethernet RJ45 connector through a LAN8720A PHY chip. The dual-core ESP32 provides a wide range of GPIO, ADC, PWM, SPI, and I2C pins, enabling the Network Interface Module to adapt to various tasks throughout the sorting process. For example, individual modules can relay conveyor velocity data or control the gantry motors. Durability and thermal performance were also key considerations, as the recycling center environment is typically hot, wet, and dirty. Therefore, the Network Interface Module was designed with a protective enclosure and active cooling using fans to maintain safe operating temperatures. Heat sinks were attached to the LAN8720A PHY chip to improve heat dissipation. The module also features an LCD display that provides operators with important system messages including fault codes and critical data. All of these features are integrated into a compact, robust Network Interface Module that balances performance, reliability, and cost.

The Network Hub serves as the backbone of the sorting system, managing data exchange between the Network Interface Modules, image processing system, and conveyor control system. The hub is powered by a low-cost, high-performance Raspberry Pi 5, paired with an 8-port Ethernet switch that interconnects all networked modules. The Raspberry Pi 5 hosts the Message Queuing Telemetry Transport broker, a lightweight, flexible publish/subscribe network protocol used for reliable real-time communication. The Raspberry Pi also provides a centralized platform for the Network Interface Modules to offload computationally intensive tasks, ensuring a fast, efficient, and scalable communication network throughout the system.

Recommendations & Conclusions

Next Steps/Recommendations for Demonstration 1

This demonstration will enable us to study the feasibility of robotic disassembly of EV battery packs while understanding the limitations and different pack construction types that could be seen at dismantlers and recyclers. The next step is to finalize the design of the semi-automated general-purpose battery disassembly cell for demonstration with three different end-of-life batteries. One of the major challenges of this work is planning for end-of-life battery safety (ex: charged battery stranded energy as part of the robotic disassembly). This work will also study impacts of battery discharge to remove stranded energy as part of disassembly and sorting of components in value streams. After the demonstrations are complete, techno-economic analysis of material separation of EV batteries for black mass processing vs. cost to develop and operate disassembly and sorting automation will be studied. This analysis will assist with planning for transition from the lab to installation with recycling partners.

Next Steps/Recommendations for Demonstration 2

This demonstration will enable high speed sorting of consumer batteries in the waste stream. The next steps are to complete the design and assembly of the battery sorting system and then to demonstrate the overall sorting process with representative batteries from the waste stream. The techno-economic analysis of material separation for black mass processing vs. cost to develop and operate the automated sorting system will help to demonstrate the value to recycling partners at other MRFs. After the initial demonstrations with a limited number of battery classes, additional battery classes can be added as needed by training the vision system and adding more battery sorting gantries.

Conclusions

The goal of this project is to test and demonstrate emerging, viable technologies for realistic industry applications within a 24-month period that improves operational efficiency, expedites adoption, and enhances worker safety for the recovery of critical materials in batteries. With project partnerships between domestic startups, industry partners, recycling firms, LTU faculty and students, and support from Centrepolis Accelerator's team of expert consultants acting as collaborative partners, a real time review of results will expedite commercial adoption and recovery of battery materials sooner.

The challenges of dealing with end of life EV and consumer batteries in the value stream are analyzed and a demonstration of disassembly and sorting technologies is being developed to prove out feasibility. Technical capabilities balanced with appropriate techno-economic analysis will ultimately prove the viability of such methods for improving purity of waste streams for downstream processing. Safe sorting of batteries entering the end-of-life stream remains one of the big challenges for battery pack dismantlers and recycling facilities. This project will help provide insights in a demonstration of capability and highlight remaining challenges.

Acknowledgments

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