



Liam - An Innovation Story

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Overview

The electronic waste (e-waste) pre-processing recycling industry is primarily based on high volume-shredding, which limits the quantity and quality of materials that can be recovered. Liam is an Apple R&D project focused on new disassembly technologies. It utilizes a fully autonomous, clean take-apart process to liberate and separate individual components for speciality material recycling. The automated disassembly system was custom built for the iPhone 6 with the ability to disassemble 1.2 million iPhone units per year. The output components from Liam are used for investigations in end-processing recycling technologies to recover materials that cannot be recovered at desired scale or purity today. Liam represents Apple's investment in pre-processing technologies. Further innovation is required—both at Apple and in the broader industry.

Introduction

The electronic waste (e-waste) recycling supply chain is made up of three major steps: collection, pre-processing, and end-processing.¹ The focus of this paper is innovation in the pre-processing phase with the development of Apple's Liam iPhone disassembly system.

This paper assumes that recycling efforts are pursued only after options to repair and/or extend the useful life of an electronic device are deemed infeasible. As such, material recovery is the goal.

Current industry practices rely on volume-based shredding techniques—inputting whole or partially disassembled devices into an industrial shredder to break the device into smaller, and potentially more easily segregated pieces. This shredding process leaves significant room for improvement in material recovery rates and in quality and purity of recovered material.

Shredding technology was developed when electronics were much larger, and contained a smaller number of materials. Historically, electronics were comprised primarily of plastics, steel, aluminum and copper, but, the electronics industry has seen an increase from 12 elements in the 1980s to over 60 elements in modern day computers—often dispersed in small concentrations throughout the device.^{2,3} Modern electronic devices are thus not only smaller, lighter and more durable, but also contain a much broader range of materials than what shredding technology was designed to recover.

This increased use of diverse materials makes traditional shredding technology ineffective—it becomes harder to isolate a particular material from the chunks of post-shredder e-waste. Shredding whole electronics today creates a very heterogeneous mix of component pieces that are difficult to sort into individual materials.

The recovery of a specific material is determined by the extent to which it can be separated and diverted to the appropriate end-processing stream. In the most simplistic terms, recycling is a matching exercise: each individual material is sent to its correct end-processing smelter to be recovered, refined, and made available for reuse. Shredding and the subsequent limited sorting (based on magnetics, eddy currents and sometimes color separation) are often at odds with isolating materials to match the capabilities of end-processing operations.

For example, end-processing refineries that receive copper-rich fractions from e-waste recyclers are optimized to recover the copper in this material stream. Typically they will also recover the gold out of this fraction (because of its financial value). They might also be able to recover a few other precious metals (such as silver, palladium, or platinum). But the base metals (materials like aluminum, iron, cobalt, nickel, and zinc) that are present due to inefficient sorting of e-waste shred, are completely lost.

Another end-processor that specializes in the iron-rich fractions from e-waste recycling might only recover the iron and lose all of the other metals that were also in the ferrous fraction (this might include magnetic materials that stuck to the iron in the pre-processing stream).

How Can Innovations Like Liam Change This?

Liam, a line of robots that can disassemble iPhone 6, started as an R&D project with the goal of improving material recovery from end-of-use Apple products. By focusing on the pre-processing step, Apple explored solutions that could better segregate materials into homogenous streams to achieve higher quality and quantities of recycled material.

Automation was explored because of its potential to provide a clean take-apart process to meticulously “de-manufacture” an electronic product. By using automation, individual components can be removed from a device and separated into like-material component streams, instead of shredding and mixing all the material together.

The end result is individual streams of components of known material composition that can be sent to the appropriate end-processing recycler—who can then maximize material recovery.

Liam also provides a unique opportunity for Apple to close the loop on material use within Apple’s own product stream. Since many of the materials used within Apple products are of a certain grade, specification, and purity level, recycling in segregated streams can provide recycled materials at close, if not identical, specifications.

For example, it is important to get aluminum back to an aluminum recycler, but an even bigger environmental and supply benefit would be to maintain the individual aluminum grade from end-of-use product back into a new product.

Liam System



Dual-screw removal robots on the Liam line

In the design of the robotic system, there is an inherent tradeoff between level of disassembly (number of components removed) and efficiency of the system (processing time per unit). To improve the throughput of the Liam system, and to optimize the disassembly process, the teams evaluated components for environmental, social and supply risk. Apple then determined key components of interest for the Liam system. Liam removes the following components from the iPhone 6: coverglass assembly (CGA), battery, main logic board (MLB), receiver, speaker, alert module, rear facing camera, and housing.

There are currently two Liam systems—one in the United States (California) and another in the Netherlands. The Liam lines operate at an 11 second takt time—every 11 seconds an iPhone is disassembled into 8 discrete components, with each line capable of disassembling 1.2 million iPhone 6 units per year. To meet this capacity, the Liam system is comprised of 29 robots in 21 cells with dual-robots used in certain cells with particularly high cycle times.

Liam Design

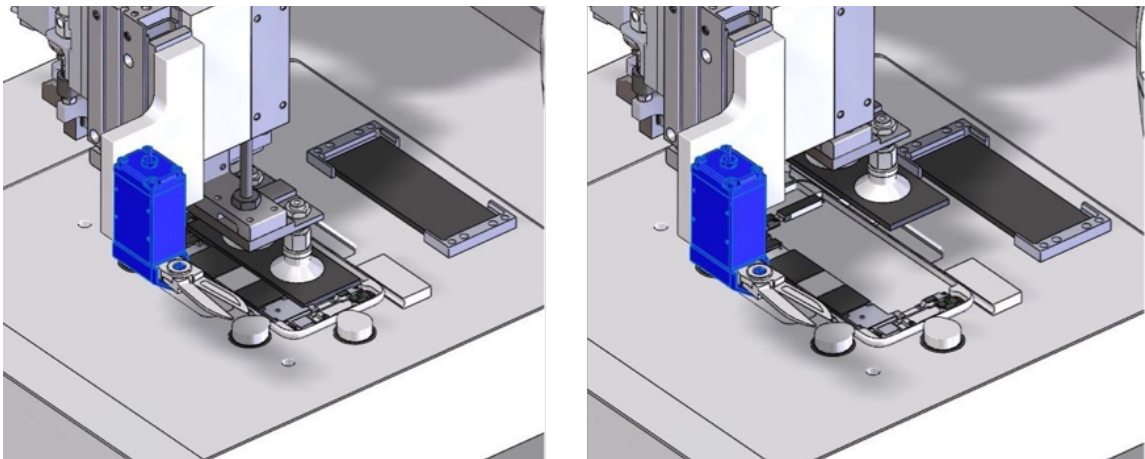
The biggest engineering challenge for Liam was how to use robotics in a system with variable incoming parts. To date, the iPhone 6 units entering Liam have been units returning from the field that are assessed to be beyond repair—these units return from the field with a variety of internal and external damages. As such, high variability exists from unit to unit, making repeatability of robotic processes extremely challenging.

To combat these unpredictable variables, the Liam team developed both hardware and software solutions to increase robustness in removal of components. The system utilizes two main types of processes to remove components: (1) end-of-arm-tooling (EOAT) such as a drill bit, suction cup or fixed tip interacting with a stationary iPhone unit and (2) direct robot handling of the iPhone unit to interact with external active tooling while performing complex coordinated motions. The EOAT on the robotic arms and external tool fixtures are all custom developed for the Liam line, as is the conveyor system that transports the iPhone units between robotic cells. Screws are removed via vacuum suction to keep the work area clear of debris, and components fall into chutes directed to isolated bins that keep the components separate for specialty material recycling.

The battery removal station is the most complex station reflecting the first process type (1) EOAT, and the speaker module is one of the most complex stations reflecting the second process type (2) external active tooling. To develop both of these stations, manual removal processes were studied and developed for high repeatability, before being replicated in robotic movements and tooling.

The battery removal station required the most overall research and development (R&D) hours due to the complexity of meeting not only engineering throughput and repeatability specifications, but also the highest environmental, health and safety (EH&S) battery safety standards. The entire process takes place inside the thermal event protection (TEP) system, which was designed to detect and prevent a lithium ion battery thermal event.

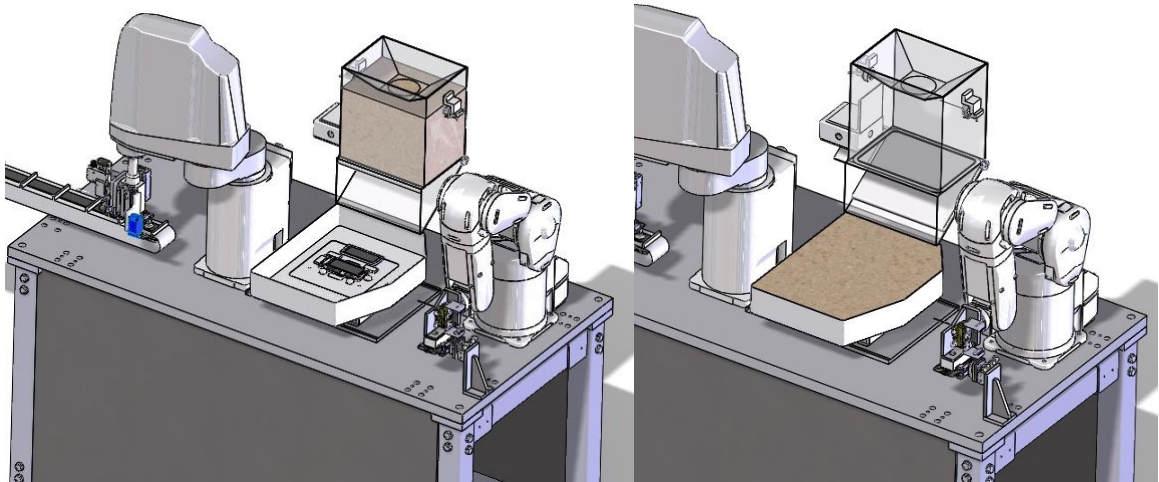
To start the battery removal process, an iPhone is placed inside a steel compartment called the "sandbox" where the CGA is removed and detached from the iPhone housing, and the subsequent screws and flex shield connecting the battery to the main logic board are also removed. Next, an external heating block with the dimensional footprint of the battery makes contact with the aluminum housing for less than 5 seconds to loosen the battery adhesive, while simultaneously a pair of vacuum suction cups pull upwards on the battery.



Battery station suction cup removal process

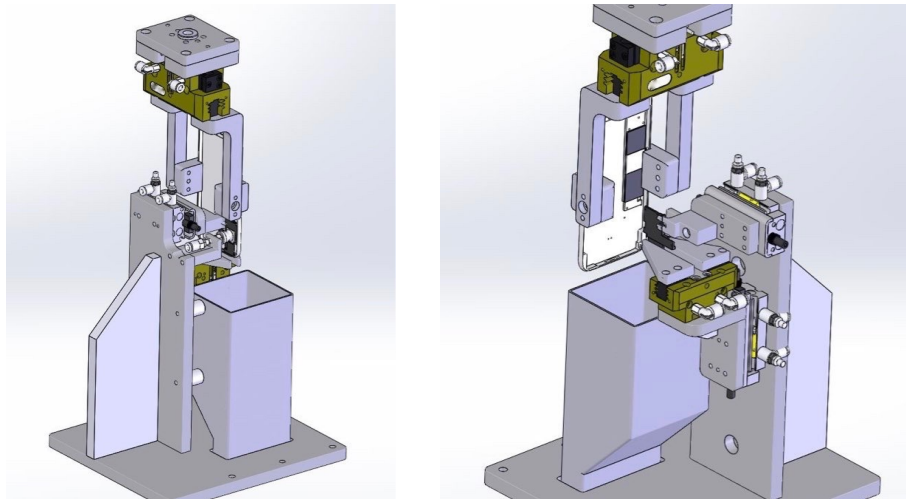
During this entire process, the heating block is kept at a temperature that limits the amount of heat transferred into the battery, such that the battery remains below a stable temperature as defined by Apple's battery engineering team. Once the battery is removed from the iPhone housing, it is placed in one of two cooling nests until it reaches the EH&S standard safe handling temperature for operators and is finally removed from the "sandbox" and placed on a conveyor belt that exits the battery system.

The battery temperature is constantly monitored for fluctuations, and a conservative "risk" temperature was delineated at which sand is deployed into the "sandbox" compartment to snuff out any possible thermal event. Sand is the universal EH&S standard for extinguishing Li-ion thermal events, and the "risk" temperature is still within the safe operating temperatures for an Apple battery.



Sandbox box system and deployment during a thermal event

Because the speaker is embedded between surrounding components, an active external tooling process was developed for this station. The robot picks up the iPhone unit and presents the unit to an external fixture that first inserts a wedge under the speaker. The robot then rotates the housing away from the wedge to pry the speaker away from surrounding components. A second gripper on the fixture clamps on the speaker while the robot departs with the housing. This allows the speaker module to be fully separated from the housing. The gripper releases the speaker module and drops it into its collection bin.



External active tooling for speaker removal

Liam Output

Traditional e-waste recycling can only recover a handful of the materials actually used in today's electronics. This is due to the challenges faced in pre-processing where highly complex electronics have to be shredded and are separated into only a few different material streams that aggregate many individual materials. Liam lets Apple address this problem by producing eight different material streams that can be sent for targeted material recovery.

As a result, end-processors can recover a more diverse set of materials at higher yields than ever possible before. Many of the additional metals made recoverable by Liam are also widely considered to be critical metals by the US Department of Energy and other government agencies.⁴

Tungsten, for example, is a very dense metal that is not recovered using traditional e-waste processing technologies. However, when the alert module is picked out of iPhone by Liam, that module can be sent to companies that specialize in recovering tungsten. The recycled tungsten can in the future be used to manufacture new tungsten carbide tools, new counterweights in alert modules, and as input material to superalloys. The acoustic modules in iPhone contain magnets made of the rare earth metals neodymium, praseodymium, and dysprosium. During traditional pre-processing, these highly magnetic materials disintegrate into fine powder and are lost to the ferrous fraction from which they cannot be recovered using today's technology. Liam enables Apple to send the acoustic modules to companies who specialize in converting rare earth magnets into the raw material needed to make new magnets.



Sorted components post-disassembly using the Liam system

Conclusions

While still an R&D project, Liam is a critical step in the journey toward establishing a closed-loop supply chain for Apple. It is also a vehicle to drive innovation in the recycling industry. By providing high-quality, separated materials to end-processors we hope they can explore and invest in new ways to recycle these materials from electronics in the future. Liam also enables a greater number of materials to be recovered from e-waste, allowing manufacturers to have more control and transparency over where those materials end up. These cleaner material streams allow Apple to investigate end-processing recycling technologies that maximize the quantity and quality of material recovery, which would otherwise be limited by traditional shredded e-waste output. As a result, companies like Apple can better direct the flow of this recycled material, ensuring it ends up with manufacturers who can use it as input for new devices.

Design of the disassembly process by the manufacturer may make sense for many of these reasons. While designing products to be easy to disassemble has gained interest in the e-waste recycling space, if shredding remains the pre-processing strategy of choice, this negates realizing the full benefits of such an approach. In addition, there are, thus far, significant trade offs between ease of manual disassembly and durability of a device.

Liam is one way to challenge whether such tradeoffs are required. Liam also helps put more recycled material into the market, so that less virgin material is mined from the Earth. For materials like rare earths, a recycled material supply does not yet exist at sufficient volumes, so discrete disassembly is the first step to enable a recycled materials market to be developed. Recycling, and Liam specifically, are part of the larger vision to build supply chains that continue to reduce, and even make positive, Apple's environmental impact on the world.

The Liam project was designed by Apple as one way to address material recovery challenges and to increase use of recycled content in new devices. Automated disassembly is advantageous since the clean take-apart process provides homogenous component streams. These like-materials can be sent directly to the appropriate end-processing recycler; however, automation is not the only path forward to improving the disassembly and therefore recyclability of end-of-use electronics. There are other innovations to be explored that can meet the same end-goal to improve the retention of the maximum value of a product for another use cycle.

What is ultimately important is that manufacturers and recyclers alike continue to invest in technologies that recover the full spectrum of embedded materials, and that we collectively prioritize technologies that do not result in down-cycling and degradation of valuable materials.

¹Chancerel, Perrine, et al. "Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment." *Journal of Industrial Ecology* 13.5 (2009): 791-810.

²Reck, Barbara K., and Thomas E. Graedel. "Challenges in metal recycling." *Science* 337.6095 (2012): 690-695.

³Committee on Critical Mineral Impacts of the US Economy, Committee on Earth Resources, and National Research Council. *Minerals, critical minerals, and the US economy*. National Academy Press, 2008.

⁴U.S. Department of Energy, "Critical Materials Strategy." December 2011.