**Learning what is in Electronics Waste**

***Matt Travers & Howie Choset, Carnegie Mellon***

Electronics waste (e-waste) poses a huge environmental problem as a majority of electronic devices today contain batteries and other materials which simply cannot be “thrown away.” Sustainability is also a factor, as rare materials today, more than ever, become more difficult to obtain from natural sources. Therefore, this work supports the belief that we need to make a better effort to efficiently and safely extract materials from existing e-waste. However, “e-waste recycling,” in its current form, involves a tedious process where a person manually opens a myriad of products to remove batteries, so that the resulting material can be safely shredded (i.e., without creating a chemical fire), before being sent to a materials recovery facility (wherein the purity of any recoverable materials generally goes down). This work is therefore mind-numbing, dangerous, time-consuming, and unsustainable. To make matters worse, the challenge in extracting e-waste grows more and more difficult as the demands for more compact devices grow. Therefore, Apple and Carnegie Mellon have embarked on a collaboration that will develop reliable automation to reduce the burden on people performing material extraction, while at the same time making the e-waste recycling process more time- and quality-efficient, as well as safer and more robust.

There is no doubt that this work will be transformative, but one must ask: why reliable automation, that could be transformative, does not already exist for e-waste recycling? We believe that a major part of the challenge, which has not been overcome by basic and applied researchers, lies in the enormous amount of variation in what is received at an e-waste recycling facility every day, all day. Today, industrial automation *could,* in theory, be trained to handle (e.g., identify, sort, present to tooling, *etc.*) a high variety of different items by pre-programming every potential item, in any condition, that might be encountered at a recycling facility. However, practically this is obviously not possible. Therefore, the proposed work seeks to develop a rigorous means of automating the process of learning how to handle new items and unexpected scenarios within the context of e-waste recycling. This type of automated generalization, i.e., adaptation to new situations, within this context does not currently exist, and therefore is the key technology to effect large impact on e-waste recycling.

The scope of the proposed work, described here, focuses on a key capability that is necessary for e-waste recovery automation: determining the components and materials, as well as their location, that lie inside an arbitrary electronics item. The envisioned system consists of two primary components: 1) A visual recognition system that identifies known classes of e-waste items and registers them to a database of three-dimensional, CAD-like models representing the mechanical composition of the items; and 2) For items not recognized by the visual recognition, a system that singulates and scans the item and builds a three-dimensional model of both the interior and exterior of the item. These models will include both geometric information as well as the semantic identity of different components and raw materials within a given item. These models will then be used to update the running database such that, if seen again, the item will be successfully identified and linked to its 3D model. The output of this system then supports any downstream mechanisms and tooling that aim the physically remove materials form the item. This type of manipulation is outside the scope of this current work, but we see the system to be developed here as providing the necessary input for such a system.

We propose to organize work toward the goal to develop a self-contained system that visually registers e-waste to three-dimensional models around four main technical thrusts:

**T1: Visually Registering Phones to known 3D Models**

**Sensor: Visual**

**Throughput: Very High**

The objective of T1 is to establish a baseline recognition system that uses publicly available data to help build a searchable database of CAD models associated with different electronics items. This work will initially determine models of electronic devices at the component level. Initially, we will use CAD models we can readily obtain and form a small database that links the 3D model data to a particular class label that is unique to the item. We will then develop and train a visual identification system to recognize each of the items for which we have models. This initial work will support the identification system for known items: this system recognizes known items, generates the correct class labels associated with them, uses the labels to search the database of models, and finally associates the correct model to the items once found as they passes through the system (e.g., on a conveyor belt to be presented to tooling). We use vision as the primary sensor for this thrust because vision provides data at high-speeds, which in turn allows use to register three-dimensional models to different electronics items at high-speeds.

**T2: Handling Imperfect Models and Edge Cases**

**Sensor: 2D X-ray**

**Throughput: High**

The T1 baseline recognition system, which uses available data, is the necessary start, but we must consider when known items do not line up with our existing models and when unknown items are encountered. Therefore, thrust T2 specifically addresses the scenario of what happens when a physical item is a class match, but its three-dimensional form does not match necessarily match our stored model (e.g., parts have been replaced)? The next thrust T3 handles the situation where an entirely new class of item appears for the first time.

The type of “model mismatch” this thrust addresses, where an item’s exterior shell matches a given class, but its structure has been modified, could occur due to several different scenarios. For example, an item may have experienced some sort of serious damage or physical deformation; its internals components might have been replaced with aftermarket parts; it could be a counterfeit; *etc.* To address this class of issues as well as maintain a high throughput, this thrust requires a 2D X-ray sensor. Realistically, there is no other way to more quickly identify and recognize damage, internal tampering, faking, *etc.* than 2D X-ray, as this imaging technology can see through conductive material. In this thrust, we intentionally are not going to use a 3D X-ray machine, as acquiring images and processing them in real-time is not possible. We therefore propose that, given the 2D X-ray, we would not be able to necessarily create high-fidelity maps or gain any direct 3D knowledge, *etc.*, but we would be able to see if any damage to the item might have caused its internal structure to deform, it parts didn’t match those in the 3D model, or if the none of the internal structure matches and the phone is a counterfeit. Given the ability the identify new items or known items in a new state, we intend to develop a simple reasoning system that inspects each case and either decides the variation between the observed item and nominal model are close enough that downstream problems are not likely to occur, or decides to isolate the item for further inspection.

**T3: Automatically Generating New 3D Models and Registering them to Images**

**Sensor: 3D X-ray**

**Throughput: Low**

Any practical system must “adapt” and “learn” as it goes. Any sorting system that assumes that it will encounter a fixed number of electronic products is clearly limited. A simple Safari search reveals the number of available electronic products seems boundless. No system can start with *all* CAD models programmed in; moreover, many products experience wear, damage and deformation, making their original CAD models useless. To this end, this work proposes to develop a framework that will automatically generate high-fidelity, three-dimensional models of the interior and exterior of unknown or unrecognizable E-waste items. Here, the proposed work relies on the use of a 3D X-ray scanner as a sensor, as it is the only option available that can image both the internal and external structure of a given item nondestructively. Given one of these 3D scans, we propose to develop a modeling framework that will produce a CAD model that is effectively indistinguishable to those in the existing database The proposed framework will transform the raw image data into a sematic and geometric map of the item that effectively serves as a newly generated CAD model. In other words, the 3D image will be transformed into a map that contains information such as, “the pixels starting at (x1,y1,z1) and spanning to (x2,y2,z2) represent a battery.” The framework will function by initially collecting 3D X-ray data for classes of phones with known CAD models. We intend to use this data to train, in a supervised fashion, a discriminative network that takes in raw X-ray images and outputs desired models. Once generated, the newly generated models will be used to re-train the above-described visual classifier to recognize and correctly associate a 3D model to the item in question if seen again.

**T4: Robust, Adaptive, and Integrated Visual Registration**

**Sensor: Mixed**

**Throughput: Variable**

Thrusts 1-3 create components of a pipeline to: 1) Visually identify different e-waste items and search a database to find corresponding 3D CAD models; 2) Quickly determine if the pre-existing CAD models actually match a given physical e-waste item; and, 3) Automatically generate a new CAD models when none of the pre-known models matches a given item (e.g., a known item with severe damage, a new item class for which no prior model is available, *etc.*). These capabilities are necessary to create a truly self-contained system for classifying and registering 3D CAD models to e-waste at very high throughputs. However, treated as isolated tasks, these capabilities do not alone solve this problem. Therefore, this work proposes to view the explicit integration of capabilities made possible by T1-T3 as its own task, warranting an additional, explicit technical thrust. Therefore, the goal of this task is to bring together a single, cohesive demonstration of a composite system that executes a specific sequence of tasks:

1. (T1) Visually scan e-waste items as they move past a fixed sensor platform on a conveyor belt
   1. If the item is recognized, it passes to the 2D X-ray scanner (T2)
   2. If the item is not recognized, it passes to the 3D X-ray scanner (T3)
2. (T2) A 2D X-ray creates an image that is compared to a known 3D model
   1. If the 2D scan “matches” the 3D model, the item passes on to a physical sorter
   2. If the 2D scan does not match the 3D model, the item passes to the 3D X-ray scanner (T3)
3. (T3) A 3D X-ray scan is used to produce a high-fidelity 3D model of an unknown item
   1. The 3D model is used to update the running database of electronics models
   2. The “convex hull” of the 3D model is used to “retrain” the visual classifier to recognize the new item and cross reference its label in the database.
   3. The item is returned to the beginning of the system, ultimately to be sorted

Note that the integration of T1-3 can then serve as a front end to sorting. Specifically, the outputs of the proposed system are classified labels for arbitrary E-waste items and as such, serves as the necessary input for a future sorting system. The design and prototyping of such a sorting system can be the topic of future work in the Apple-CMU collaboration.

Milestones:

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Tasks | Thrust | Month | | | | | | | | | | | | |
| 1 | 2 | 3 | 4 | | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Develop initial database of CAD models | T1 |  |  |  |  | |  |  |  |  |  |  |  |  |
| Link visual classifier to models in database | T1 |  |  |  |  | |  |  |  |  |  |  |  |  |
| Procure a 2D X-ray machine | T2 |  |  |  |  | |  |  |  |  |  |  |  |  |
| Determine how to register 2D X-ray scans to 3D models | T2 |  |  |  |  | |  |  |  |  |  |  |  |  |
| Develop state machine that reasons about the quality of match between 2D scans and 3D models | T2 |  |  |  |  | |  |  |  |  |  |  |  |  |
| Procure a 3D X-ray machine | T3 |  |  |  |  |  | |  |  |  |  |  |  |  |
| Collect data set to train X-ray classifier for semantic map generation | T3 |  |  |  |  | |  |  |  |  |  |  |  |  |
| Train X-ray classifier and begin testing | T3 |  |  |  |  | |  |  |  |  |  |  |  |  |
| Prepare final integrated demo | T4 |  |  |  |  | |  |  |  |  |  |  |  |  |

**Budget:**

**Total Personnel Costs 193,287**

**Total Hardware Costs 450,000**

**Total Travel Expense 3,548**

**Total Direct Cost 649,733**

**Facilities & Administration 111,334**

**Total Project Cost $762,518**