Real-time monitoring for corona-electrostatic separation in recycling waste printed circuit boards

A Major Qualifying Project proposal to be submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree of Bachelor of Science.

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Abstract

Due to the large demand for electronic products, large amounts of electronic waste are being generated all around the world. Almost all of these electronic products contain printed circuit boards which form an essential part of the technology. Printed circuit boards are made of different materials including precious metals such as gold and silver, and the recovery these precious metals has proven to be a profitable industry. However the methods often used by small workshops and informal backyard set-ups include combustion, hydration and pyrolysis which have proven dangerous as they generate a lot of environmental pollution. Humans are often exposed to large amounts of cadmium and mercury which are extremely harmful. It is imperative that new and safer methods of recovering these precious metals be adopted. Corona electrostatic separation (CES) is a method used that is safe to humans and does not generate secondary pollution. However, this technology was invented in developed countries and is often too expensive and too costly to maintain for the average worker in developing countries. China has begun working on a similar technology; however, this technology is still in its infancy. This corona electrostatic separation technology in China is less expensive and uses less power so that it can be available to vendors in developing countries. This more affordable corona electrostatic separation technology has been successful in recycling waste printed circuit boards; however, there are still some problems that exist with the stability of the technology. High voltage breakdown and particle aggregation have been identified as the problems which affect the stability of the system and therefore affect the effectiveness of the separation process. This paper provides a study of a real-time monitoring system that will allow for the continuous monitoring of the separation process. The sample material, collected as middling in the separation process, was collected and monitored by a Visual Interface (VI) program written by LabVIEW. The monitoring system has two parts, the hardware and software platforms. The monitoring system requires the hardware and software to work together concurrently to ensure real-time results. The inability to connect the two platforms did not mean the project was not a success as independently the hardware and software showed the ability to operate as they should. A simulated signal revealed that the software would be able to set off alarm signals should there be accidents or disturbances to the separation process. Lastly, experiments were proposed that could improve the existing CES process by eliminating instability in the process.

Acknowledgements

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Thank you to the interdisciplinary and Global Studies Department of WPI for making conducting research in China a reality. I would like to thank them for their organization and the support while preparing to travel abroad. I would also like to thank the Chemical Engineering Department of WPI for their arrangement for an opportunity like this to exist in their department. Without their hard work and dedication, this project could never have been possible.

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1.0 Introduction

1.1 Motivation

Printed circuit boards (PCB) are found in various technological devices such as cameras, televisions and computers. A dramatic increase in the demand for electronics in recent years, prior to 2007, has led to an increased worldwide PCBs manufacturing by 8.7 % in 2008 (1). The figure is much higher in Southeast Asia (10.8%) and mainland China (14.4%) (1). In mainland China, the total production value of the PCB manufacturing industry was $10.83 billion in 2005, only next to Japan, and was more than $12 billion in 2006 (1).

Owing to greater demand for electronic goods, new technological innovations continue to accelerate the replacement of equipment, leading to a significant increase of waste PCBs (2). Due to this phenomenon, the large amount of electronic waste (e-waste), also known as waste electric and electronic equipment (WEEE), has become a very important subject of concern, particularly their treatment (3). Large amounts of electronic waste have been generated, with China producing 100 million tons each year (3) as well as an additional large number which flows into China each year. Much of this waste is from waste PCBs (4). In PCBs, there are large amounts of precious metals, toxic materials including heavy metal, PVC plastic and brominated flame retardants(5).

1.2 Domain

A number of methods have been adopted in the aim to recover precious metals from PCBs. Backyard producers, who are individuals that have set up informal precious metal retrieval processes, saw this increase in the demand for technological devices as a way to generate income, and so many established businesses recovering precious metals from PCBs. However, these methods are dangerous and involve chemical methods which often emit toxic liquids or gases that generate secondary pollution during the precious metal retrieval process (3). These harmful methods are common due to the high cost of pollution-free processing (4).

Apart from the use of chemical methods as a way to recover precious metals, mechanical methods can be used which have proven to emit little to no pollution (2). Mechanical processes, such as shape separation, density-based separation, and electrostatic separation are widely utilized in the recycling industry. Metals are completely stripped from nonmetal base plates and the waste PCBs were scraped to small particles below 0.6 mm (1).

Corona electrostatic separation (CES) is an effective and environmentally-friendly method for recycling PCBs that have been reduced to small particles by crushing. Small printed circuit board particles are fed into the corona electrostatic separation machinery which separates the particles into metals, nonmetals and middling (mixture of metal and nonmetal). The extreme difference in the density and electrical conductivity between metallic and nonmetallic materials provides an excellent condition for the application of corona electrostatic separation in PCBs recycling according to Li et al (1). However, there are still some notable problems, which affect the stability of the separation process, which include high voltage breakdown and particle aggregation (14). This high voltage breakdown is in the form of electrostatic discharge that occurs when an electric current flows between two objects at different electric potentials. Balance between the production capacity and the separation quality is also another area of concern (1). The corona electrostatic separation method is an effective method for separating small particles through the use of roll-type corona electrostatic separators. The CES does not produce wastewater or gas during the process and it has high productivity with a low-energy cost making it a highly desirable process (5).

With the corona electrostatic separating process, in a sample study 70% of recovered materials were nonmetallic and metallic materials as the remaining materials. The metallic materials range from precious metals such as gold and silver to less precious metals such as aluminum, lead and tin. Generally, the nonmetallic materials are an epoxy resin or phenol formaldehyde resin, glass fiber, and brominated flame retardant (8). The treatment of these nonmetallic byproducts was as important as the treatment of the metallic products. The production of phenolic molding compounds (PMC) and nonmetallic plates (NMP) were ways in which these nonmetallic byproducts could be reused (8). Great success has been accomplished with separation methods with the use of electrostatic separation.

The treatment of then nonmetal products ensured that the CES process produced little to no by-products that could be classified as waste. Recycling of all separation products acted as another avenue to generate revenue from waste material (9). After paying attention to the treatment of nonmetals, the next step was to monitor the corona electrostatic separation process to optimize separation efficiency and purity.

1.3 Goals and Objectives

My project was to investigate a real-time monitoring system that will detect anomalies in the corona electrostatic separation process. The monitoring system will detect the high voltage breakdown and particle aggregation which have been identified as factors that affect the stability of the separation process. The monitoring system will consisted of a hardware and software platform which will work together to present real-time data of the separation process. The hardware consisted mostly of the mechanical separating process equipment while the software platform was a Visual Interface program ran in LabVIEW software. The aim was to make the corona electrostatic separation process intelligent, to be able to identify an abnormality in the performance of the system and perform an action to correct it.

2.0 Background

2.1 Waste Printed Circuit Boards

A Printed circuit board (PCB) is a thin plate on which chips are placed (See Figure 1). Chips are small pieces of semiconducting material usually made out of silicon. These chips can contain millions of electronic components which are known as transistors. When several numbers of these chips are situated on an electronic board, it is called a printed circuit board. Many computers have one or more boards contained inside them, often named adapters or cards (9). These printed circuit boards (PCB) scrap have precious and non-precious metals.

Figure 1: Waste Printed Circuit Boards (1)

These waste printed circuit boards contain precious and nonferrous metal resources and there is therefore an economical drive to retrieve these metals (4). Nonferrous metals include copper (Cu), lead

(Pb), and tin (Sn). PCBs have a purity of more than 10 times that of content-rich minerals (10). As a result, there are masses of backyards and small workshops which began retrieving these metals using simple methods which pollute the environment (9). These simple methods include chemical methods which consist mainly of pyrolysis, combustion, hydration, and electrolysis (10). When combustion and pyrolysis are used, large amounts of atmospheric pollution are created, through the discharge of harmful substances such as furans and dioxins. Hydration and electrolysis produce huge amounts of waste acid liquid during the recycling process and this acid liquid needs to be carefully disposed, which is rarely done (9). The workshops and backyard producers use inexpensive and primitive methods such as acid washing and burning. These methods are environmentally unfriendly and hazardous which result in grave environmental pollution such as the release of waste acid liquids, dioxins, and furans, in waste electric and electronic equipment treatment areas (3).

There is significant environmental and human health risk presented by electronic waste (including waste batteries, waste printed circuit boards, waste liquid crystal displays, etc.). The impact on humans and the environment has aroused the attention of many researchers and has generated a strong reaction from the government in China (4).

With all the concerns about the rise in the number of waste printed circuit boards, a new process was devised which involved mechanical crushing, screening, drying and electrostatic separation via corona discharge(2).

2.2 Corona Electrostatic Separation

Corona electrostatic separation is an efficient and environmentally-friendly means for recovering metals from waste printed circuit boards(2). Electrostatic separation, defined as “the selective sorting of charged or polarized bodies in an electric field (3),” presents an effective way for recycling metals and nonmetals from waste electric and electronic equipment without or with minimal negative impact to the environment, especially for waste printed circuit boards (3). The use of corona electrostatic separation has been well studied in the minerals-processing industry. The electrode system design which includes a fundamental and practical aspect has been studied by Iuga et al (12). Looking at the vast differences in properties of metallic and nonmetallic materials such as density and electrical conductivity, there exists an excellent environment for corona electrostatic separation to be carried out.

During the year 2006, the use of corona electrostatic separation was still in its early stages (2). Early work showed that “1. A two-step crushing process could completely strip metals from base plates; 2. The effect of aggregation opposed the production on fine powders; 3. Particle sizes between 0.6 and 1.2 mm are most feasible for separation in industrial application.”(1) (See Figure 2 below).

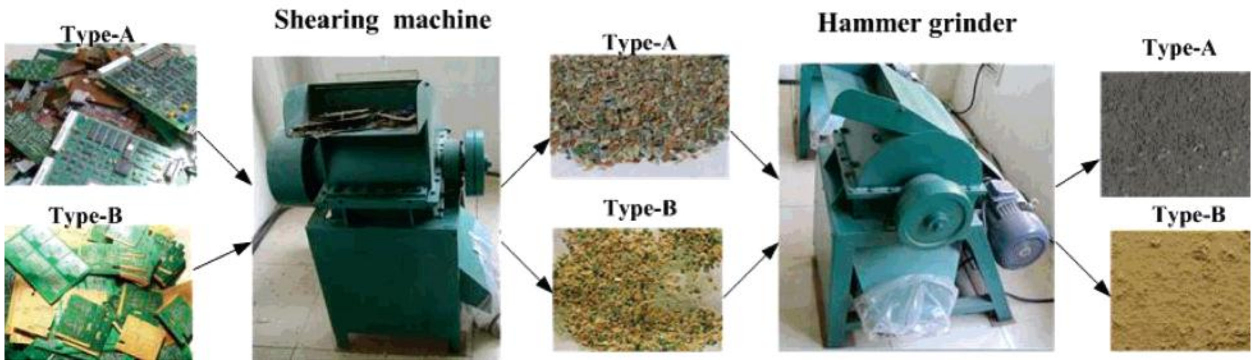

Figure 2:Two-step crushing flow chart (1)

Before the separation can take place, a pre-processing method may be adopted. One example description follows, as taken from Li et al. The purpose of the process is to get the PBC boards into particles of homogenous dimensions. This process includes crushing, screening and drying. The reinforced resin and metal components in the PCB boards such as copper wires and joints have a high hardness and tenacity. Due to these properties, a high-speed shearing machine may be used for general-purpose crushing (2). The second crusher has a hammer grinder which was especially designed for PCBs. The materials coming out of the hammer grinder are screened by the electric shaker where the delaminated material was separated according to size as seen in Figure 3 and 4.

Figure 3: Two-step crushing flow chart (1)

Figure 4: Crude particles (10×10 mm) (2)

The final stage of the pre-processes stage entails heating the respective material to 100 °C in a drying stove for duration of three hours. This step aims to remove the moisture content of the samples to 0% (2). After the pre-process is completed, corona electrostatic separation is introduced which includes a high voltage electrostatic field being generated by a corona electrode and an additional electrode as seen in Figure 5(2).

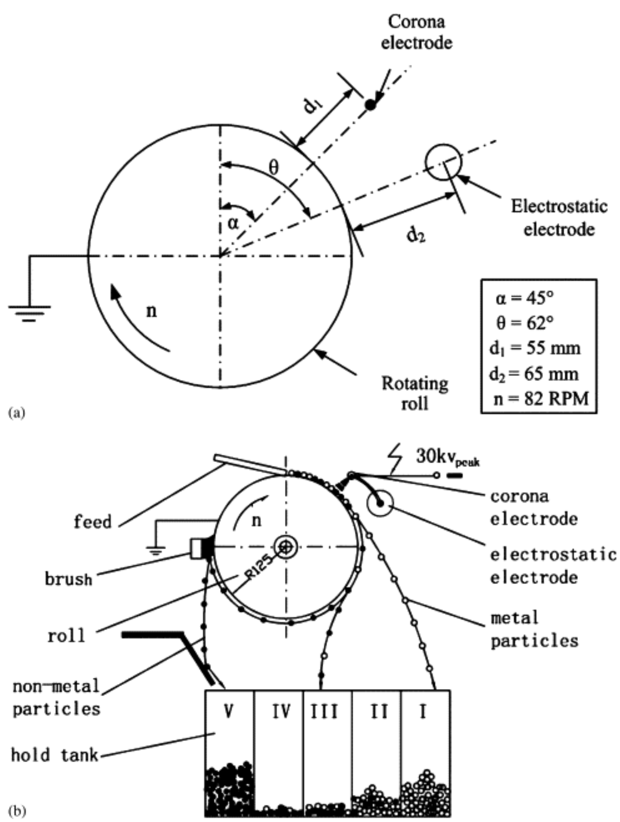

Figure 5: Operating parameters (a) of corona electrostatic laboratory separator (1)

In the corona electrostatic separation process, metals and nonmetal particles are electrostatically induced when entering a field and are “ion bombarded” with a corona charge (1). A corona charge is an electrical discharge brought on by the ionization of a fluid surrounding a conductor but conditions are insufficient to cause complete electrical breakdown (2). Metal particles are discharged rapidly to the earthed electrode while the charged nonmetals on the other hand are “pinned” by the electrical image force to the rotating roll and rotate with the roll until they finally are released into the holding tanks. The separation is achieved due to the different electric field forces working on the metal and nonmetallic particles (2).

With corona electrostatic separation, particle size is important. A particle between 0.6 and 1.2 mm is feasible for industrial applications while fine powders are unsuitable for electrostatic separation. Hence adjusting the operating parameters of crushing machines will increase the efficiency of retrieving particular particle quantities (4). (See Figure 6).

Figure 6: Metal and nonmetal products from a Corona Electrostatic Separator (1)

2.3 Computer simulations of separating mixtures of metal particles from waste printed circuit boards by electrostatic separator

Continuous improvements were made to the existing electrostatic separators to eliminate the problem of some valuable metals such as aluminum, zinc and tin with low content in PCB being lost during the smelting process. This results in these resources being wasted. A new method, the roll-type electrostatic separator (RES) (See Figure 7) presented itself as a way to solve to recover low content metals in waste PCBs (14). A theoretical model was built through the computation of an electric field and then particles analyzed in a similar manner as the previous simulation using the MATLAB program.

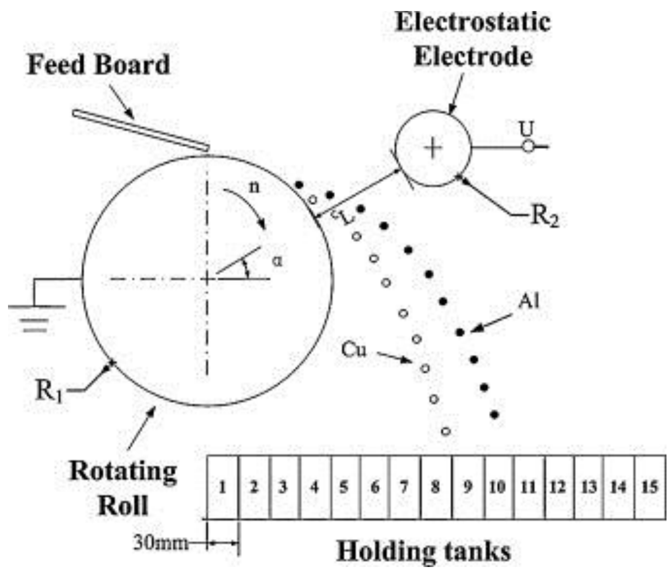

Figure 7: Diagram of roll-type electrostatic separator (5)

The MATLAB computer program that was designed to simulate the process of separating the mixture of metal particles showed that roll-type electrostatic separator (RES) was a good method. The program showed that the simulation could be used as a model that could guide the RES to separate different metals from waste PCBs with better efficiency. Li et al. states that, “The impacts of electrical, material and mechanical factors to the particle trajectory were analyzed and the optimized operating parameters for separating copper and aluminum particles were got”(14).

2.4 Automatic Line - Industrialization Technology

The final stage of the research for the proper retrieval of precious metals has involved technological industrialization. This research contained an automatic line without negative impact to the environment for recycling waste printed circuit boards (PCB) in industry-scale(1). The automatic line, which is an industrial size version of the corona electrostatic separation machine, is pictured below in Figure 8. The automatic line technology involves four parts: multiple scraping, material screening, multiple-roll corona electrostatic separator, and dust precipitation as seen on Figure 8. Pollution and waste were reduced as the metal and nonmetal products of the output were completely reused. The automatic line when compared to production lines from developed countries had lower energy consumption as well as technology rationality and was cost efficient for local processors(4).

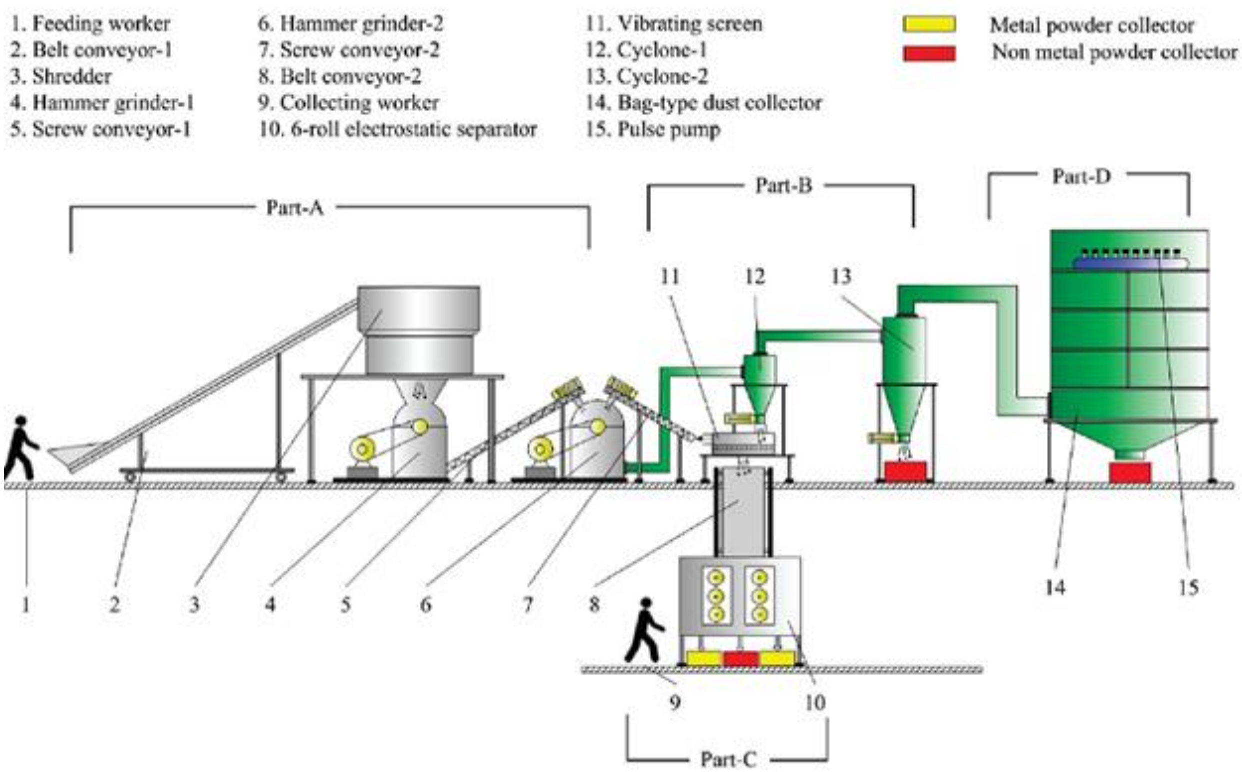

Figure 8: Whole automatic line for recycling waste PCBs in industry-scale. (14)

The first part of the automatic line entails multiple scraping. This is a very important part of the mechanical method for treating printed circuit boards. As these boards are a mixture of woven glass reinforced with resin and metal, general scraping machines cannot provide adequate metal stripping but have an abundance of waste energy(4). A number of parameters have to be considered, such as temperature. A high temperature increases the possibility of pyrolysis and as discussed earlier (6), this was an undesired by-product of CES the process. A change in the two step crushing process helped eliminate this problem. This was done by controlling the rotating speed of knives in the hammer grinder.

The next stage entails material screening. This process sorted the particles according to particle size to ensure that they were the right sized particles to proceed to the next stage as seen on Figure 13. The machinery includes a two cyclone and one vibrator screen. The suitable sized particles were +0.6-1.2 mm (4).

Although great improvements have been made in the optimization of the electrostatic separation, some problems limit the traditional single roll electrostatic separator to satisfy industrial application requirements (14). For this reason, a 6-roll electrostatic separator (triple-step separator) was used in this automatic line, as shown in Figure 9. This arrangement eliminated the balance between metal purity, production capacity (7), impact from fine nonmetal particles during the separating process,(14) and further treatment for media material (mixture of metal and nonmetal particles after separating)(12). This efficient process involves three vertical rotating rolls, with three major influencing factors to separating: construction of electrodes, position of separator board, and rotating speed of roll."(4).

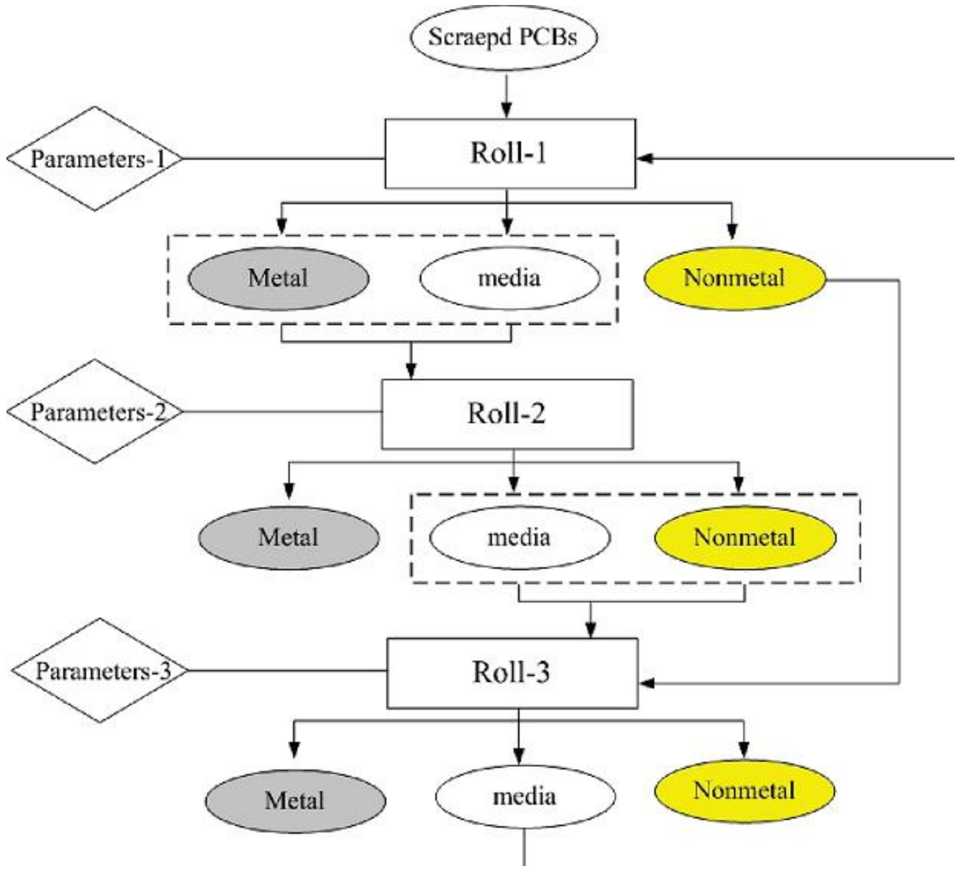

Figure 9: Flow of triple-step electrostatic separation (4)

The last stage is the dust precipitation process. This stage entailed dust collectors in the form of pulse pumps cleaning the backs and moving the dust to the collector. In this way, the dust that was flying from the crushing and screening processes was recollected and therefore could not be harmful to the workers (4).

As shown in Table 1, the traditional fluid bed production line has low "metal recovery rate", so its gross rate was lowest (4). When compared with other processes, "the process from developed countries has high power, so its gross profit was lower than the automatic line and the equipment cost was too high for local processors. Compared with other production lines, the automatic line has lower energy consumption and better technology rationality," concludes Li et al. (4).

Table 1: Comparison of the Three Kinds of PCBs Mechanical Production Line (4)

	Traditional Fluid Bed	Corona Electrostatic Separation Process from developed Countries	Automatic Line
Output (ton/hour)	0.3	0.3	0.3
Power	200	400	130
Metal recovery rate	<80%	>90%	>90%
Operators	10	4	4
Equipment Cost ($)	30 k	700 k	100 k
Environmental effects	Waste water	None	None
Maintenance cost ($/ton)	4.95	2.95	2.95
Cost ($/ton)	1422.45	1490.85	1363.65
Gross profit ($/ton)	17.55	129.15	256.35

Current work includes improving the stability of the corona electrostatic separation of the automatic line. This work will prove beneficial to improving the stability of the separating technology.

2.5 Corona Electrostatic Monitoring System

The corona electrostatic separation is a highly specialized mechanical process with many opportunities for improvement. A specific example is the nonmetal particle aggregation and high voltage separation phenomena that occur during the corona electrostatic separation process. My study focused on investigation of real-time monitoring system of the separation process to proactively identify specific areas of improvement. The separation process is in the breakdown phase, an intense volatile and speedy event, makes detection of anomalies extremely challenging. By developing controls that will feed into a monitoring system and take actions based on predefined limits, we hope to create an intelligent software solution.

Work had already begun on a monitoring technology in the WEEE department at the School of Environmental Science and Engineering Shanghai Jiao Tong University. LabVIEW software was identified as a suitable tool to effectively monitor activity during the separation process. LabVIEW is a, "graphical programming environment used by engineers and scientists to develop sophisticated measurement, test, and control systems using intuitive graphical icons and wires that resemble a flowchart" (16). This program allowed for results to be displayed in real-time, setting off alarms should anomalies occur in the system. Figure 10 below demonstrates the need and use of the monitoring system.

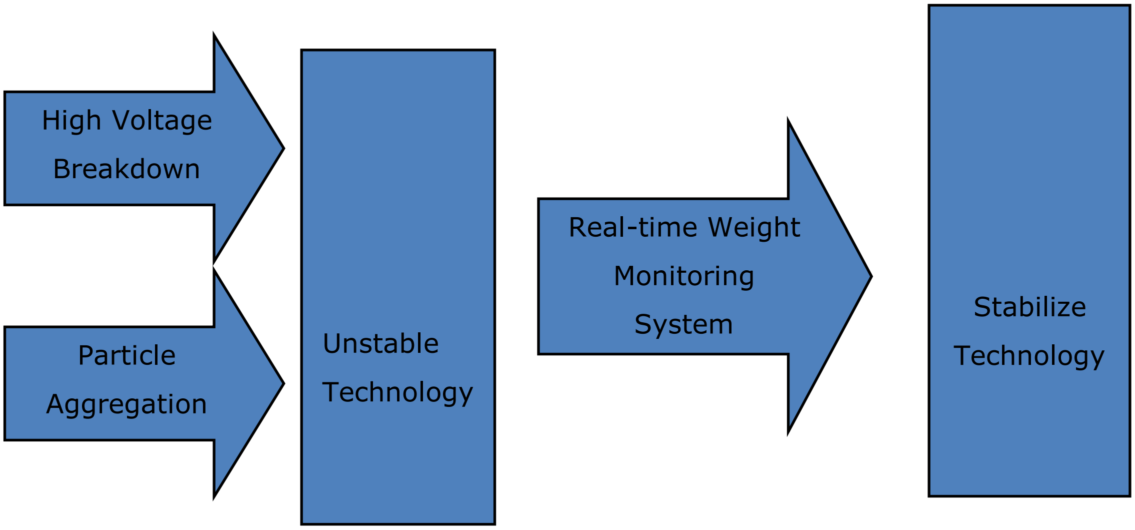

Figure 10: Need for monitoring system flow chart

High voltage breakdown and particle aggregation are the main factors that affect the effectiveness and quality of the corona electrostatic separation process. When high voltage breakdown occurs, a high voltage occurs which electrostatically charges the particles. The particles become charged and therefore attract each other. This creates larger particles which are not the optimum size for separation. Particle aggregation occurs when the particles rub against each other and become electrostatically charged and attract each other. This too causes larger particles to be created, which create unfavorable separation feed conditions. These phenomena occur within seconds and therefore do not give the operators enough time to discover the problem. The occurrence of these phenomena causes the corona electrostatic separating machinery to become unstable. The aim of the real-time monitoring system is to continuously monitor the occurrence of these phenomena and furthermore create a mechanism that will correct the malfunctions. This continuous monitoring through the combined use of the hardware, software and the LabVIEW program will help stabilize the corona electrostatic separation technology (See Figure 11 below).

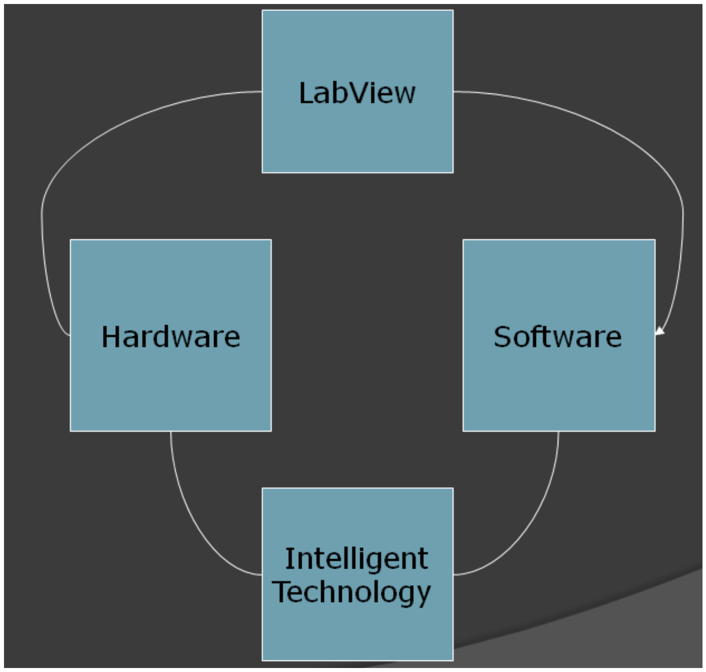

Figure 11: Flow chart showing the components of an intelligent technology

2.5.1 Software- LabVIEW Program

The software platform is, "on a basis of multitasking information handing network which is constructed by LabVIEW technology" (15). The program has analytical capabilities that can help extract the information needed to keep your system running smoothly. The majority of the methodology regarding the software entailed programming to establish control levels which served as reference points for the operation of the separation machinery. Programming was done by students and professors prior to my arrival in China.

This software is extremely convoluted and requires icons with individual functions to be placed on a palette. How the virtual instruments works is that reusable blocks of codes, which are namely functions, which have some number of inputs parameters and some number of return values are configured. When an icon is placed on a palette it is called a VI (see Figure 12). When several VIs are connected, they are called subVIs (See Figure 26). Each subVI receives an input from a source and returns the data to either an indicator or another subVI (17).

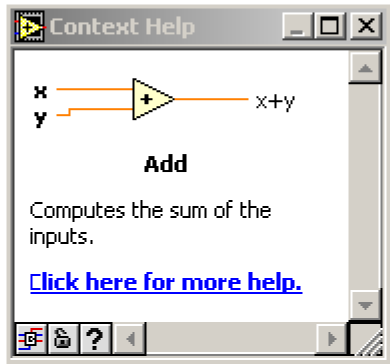

Figure 12: Single VI

For the control system, data was entered data directly into controls and we watched the output on the indicators. The subVI program seen below in Figure 26 shows the set of inputs and outputs that formed the monitoring system. Two control charts exist, the X-mR and the X-chart. In the data acquisition system, the upper and lower control levels are given by the follow equations. The control levels are shown on the man-machine interface.

2.7.1 Visual Interface (VI) Program

In a Visual Interface Program, each icon has a specific and special function that allows it to receive inputs in the form of signals. An icon will perform and action that will provide an output in the form of another signal. This signal can either set of a response, i.e an alarm, or transfer the signal to another icon in another subVI. The way in which the subVIs are connected is extremely complex but meaning can be derived from them by simply looking at a step by step analysis. When all these subVIs work together, they perform continuous monitoring, setting off alarms when there are any disturbances which occur in the separation proces. Below (Figure 13), is the complete diagram showing how the real-time monitoring system works.

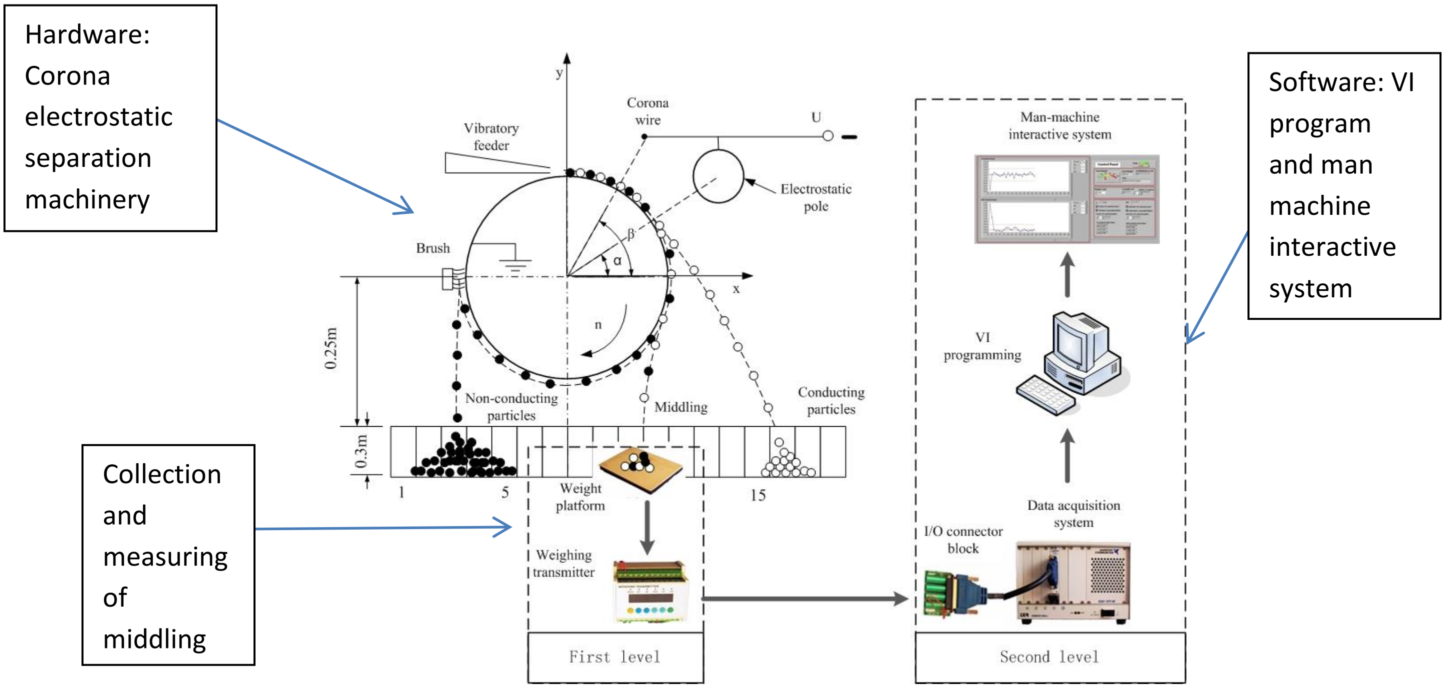

Figure 13: Hardware platform for corona electrostatic monitoring system (15)

3.0 Methodology

The two primary objectives were, to become familiar with LabView software and to create controls using real-time monitoring to ensure effective operations. Meetings were dedicated to doing several things which included examining the purpose of the project, as well as conducting experiments to familiarize me with the completed features of the system that other students had already started working with. The experiments were carried out in the Waste Electrical and Electronic Equipment (WEEE) department in the School of Environmental Science and Engineering at Shanghai Jiao Tong University.

Prior research on the technology of corona electrostatic separation had been done in the United States. Upon arrival in China, it was imperative that further research is conducted on the LabVIEW software as it was an important part of the project work in order for to fully appreciate the technologies we were working with. It was essential that I have deep understanding of how the separation technologies and the LabVIEW software work together.

As already stated, during the corona electrostatic separation process, the waste printed circuit boards are separated into metals, nonmetals and middling (combination of metals and nonmetals). Previous work identified middling as a good sample material as it reveals and monitors the process of separation as the weight of the middling is a perfect indicator of how the separation system is operating (3).

There are three parts to the real-time monitoring system. This first two exist in the hardware platform phase while the last part exists in the software platform phase (See Figure 14). The first part of the hardware is the corona electrostatic separation mechanical process. This part focuses heavily on the separation of metals, nonmetals and middling. The accumulation of middling on a weight platform will form the sample size allowing for data to be detected, read and processed in the second part of the hardware phase. The third and last phase is the display of the data on control charts which monitor separation processes.

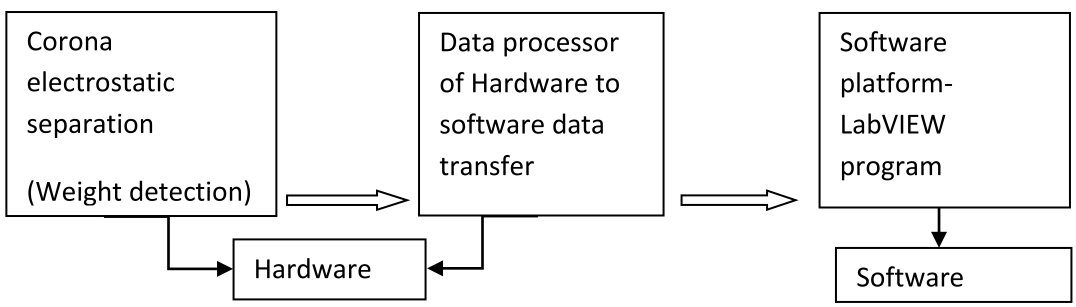

Figure 14: Monitoring system components

As the LabVIEW monitoring system works in conjunction with the corona electrostatic separation system, it was important that we ensured flawless operation of the corona electrostatic separation machinery. Connecting the hardware and the software ensured that the two platforms worked together and communicated to provide real-time results of the separation process. Figure 17 below shows all the different components of the real-time monitoring system.

The Hardware phase began with the separation of the waste printed circuit boards by the use of the corona electrostatic separating machinery. Wasted printed circuit boards come in different shapes and sizes. The circuit board consists of unwanted toxic materials which can have an impact on the environment once the materials end up in a landfill. These components are removed prior to the recycling Figure 15 shows printed circuit board after toxic components have been removed. The WEEE department receives the PCBs which already have the toxic components.

Figure 15: Waste printed circuit boards after toxic parts are removed

Before the printed circuit boards could enter the separating machinery, they had to be crushed into particles. Once the toxic components had been removed, they were now in the right form to be fed into the hammer-grinder shown below in Figure 16. When fed to the machine, broke down the waste printed circuit boards into appropriate sized particles which were identified in previous research to

be -0.456-0.3 mm (REF) (See Figure 17).

Figure 16: Waste Printed Circuit Board Hammer-Grinder

Figure 17: Metal and nonmetal material from crusher/grinder

Below is Figure 18, which shows the cabinet containing the electrostatic separation equipment. Due to confidentiality requirements, illustrations of the inside of the machinery could not be shown. The top section contains the feeder where the crushed mixture of metals and nonmetals are added for separation machinery. The top also contains one roll-type electrostatic separator which includes a brush. The middle section is where the collection trays are located. Three trays lie side by side with the metals being collected in the left tray, the middling in the middle try and the nonmetals in the right try. Lastly, we have the control box situated on the left, which contains the operational buttons for the machine which display the functions such as rotations per minute of the rotating roll.

In this process of separating metals from nonmetals, our sample material (middling) was also collected, initiating the second phase of the hardware platform phase. The mechanical breakdown of the printed circuit boards was the first stage of the hardware platform phase. The data acquisition and processing equipment represented the second phase of the hardware platform phase before changing to the software platform phase.

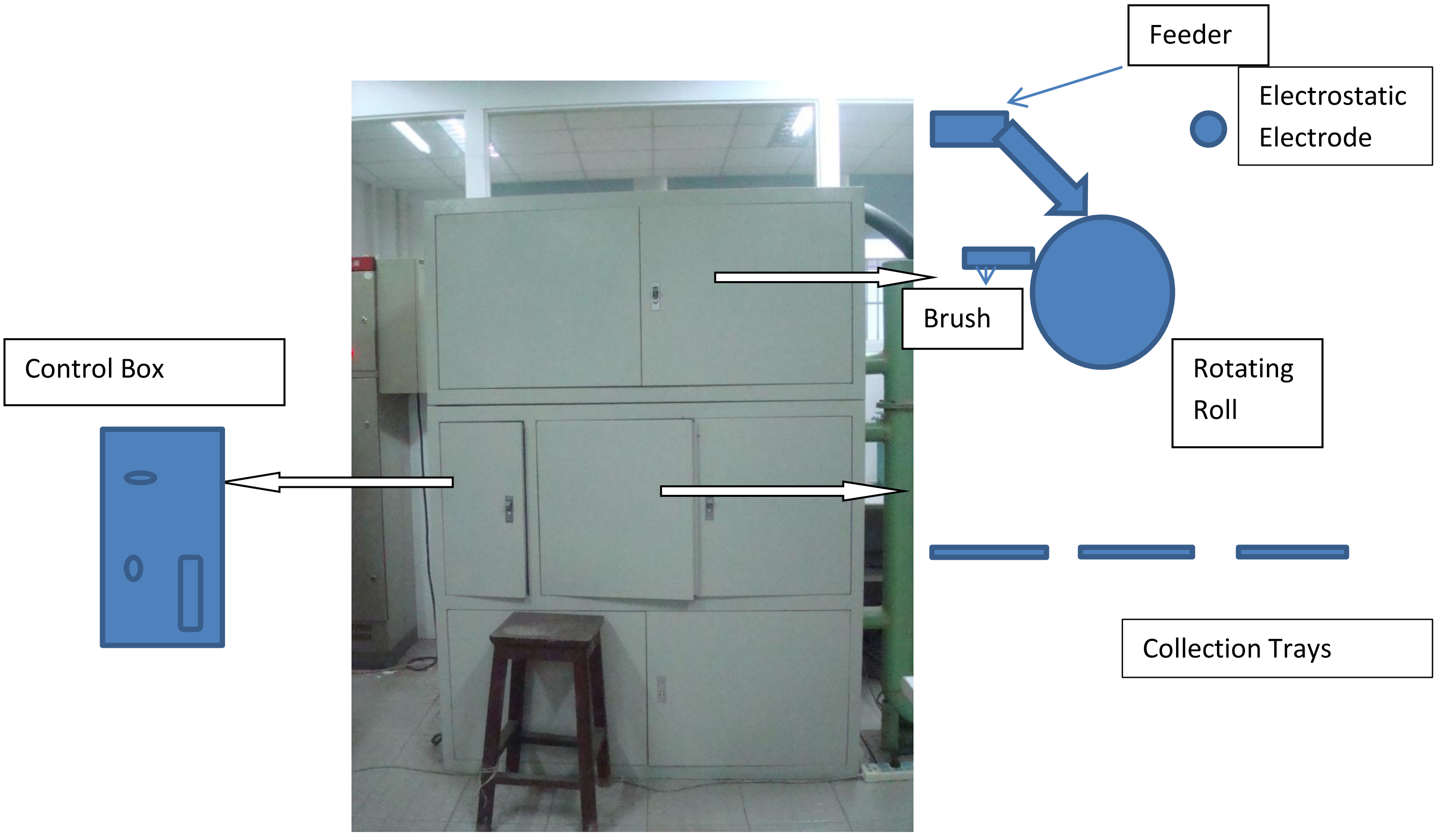

Figure 18: Cabinet containing the corona electrostatic separation equipment

Figure 19 below shows illustrates the material collected in the middling container of the corona electrostatic separating machine. The sample contained a mixture of copper, aluminum, and non-metal product which is mostly polyvinyl chloride (PVC). The accumulation of this middling on the weight platform provided a means of monitoring the present situation of the separation process. Once the middling landed of the weight platform, a signal was to be generated. A weight signal was transferred to a 4-20mA industrial current signal by the weight transmitter (15). The industrial current (A/D) was to be transferred to the digital signal by high speed acquisition card PXI-6236.

Figure 19: Middling product after separation

The weight signals were processed and transferred to the weighing transmitter which converted the signals to allow them to be read by the visual interface programming computer (See Figure 24). The man-machine interactive system allowed the data to be read in the form of control charts.

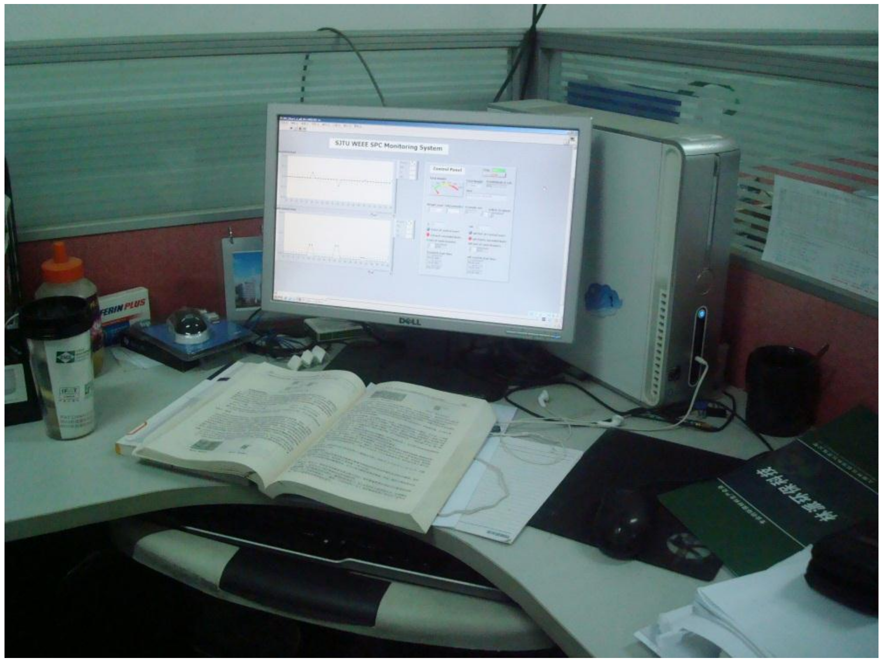

Figure 20: VI programming station in WEEE department

4.0 Results and Discussion

4.1 Real-time Monitoring System for Corona Electrostatic Separator

The project encountered a significant obstacle with hardware and software communications. Specifically the PXI card used to transfer data from the manufacturing process to our computer software was unable to function properly. Unfortunately significant time was invested to finding this problem and affected the direction of the project.

To move the project forward we developed a simulation process (described above) to verify that our notification alarms worked as expected. As we were unable to get the hardware and software working together, it was essential that we examined whether the software was working properly through the use of the simulated signal. The problem seemed to be with the chip that transforms the signal from analogue to digital signal. As with any software project, it is crucial to choose a software development process to ensure the delivery of quality and clear messages. The software therefore has to be running efficiently. The decision to run a simulation signal that would mimic a real signal transmitted from the corona electrostatic separation machinery would mean that we could rule out the possibility of the software being faulty.

After we ran the simulated signal on the block diagram, we were able to follow the activity of the signal as it travelled from icon to icon. The aim was for the signal to travel across the block diagram and to finally sound the alarm as when you look at the man-machine interactive interface below (Figure 33) the points were outside of the control levels which means that if it were a real signal the alarm would have went off.

4.1 VI Signal Transfer Process

A. Signals converted by data acquisition (DAQ) system to a weight signal were received by the subVI below in Figure 21. This subVI had a timer which was programmed to receive signals after a set period of time. The signal was received in the form of a direct current which had been programmed to give off uniform noise should the there be a disturbance in the separation system. The current sample was compressed and allowed to move onto the next subVI.

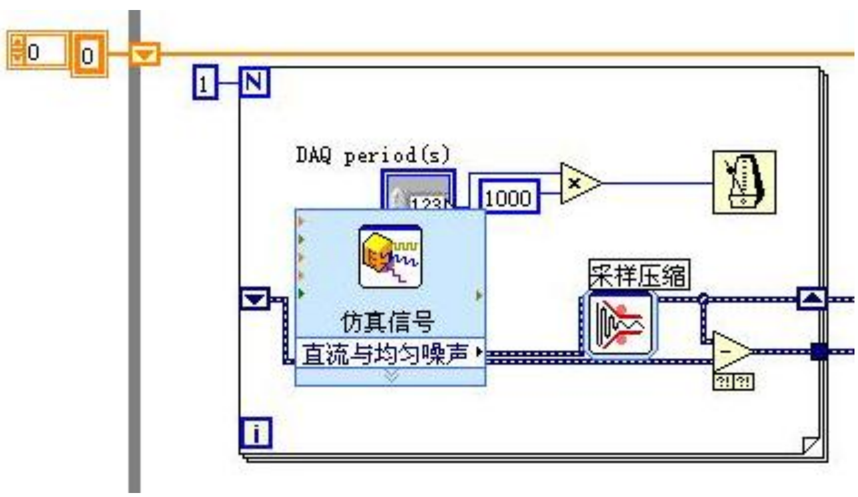

Figure 21: SubVI (A) receiving data from DAQ system

B. Signal leaving subVI A was transferred to the next subVI (B) below seen in Figure 22, which monitored the weight of the middling sample. Two areas were measured and monitored, one being the total weight of the sample and the second ensured that the total weight limit was not exceeded on the weight platform. The middling accumulation weight was written in a measurement file which is then stored in the historical data storage. This storage was very important as information stored in it can be used at a later stage as a reference for future monitoring projects. Two types of alarms were present in the monitoring system, historical data overflow and current data overflow, showing the importance of the historical data storage (15). Should either of these limits be exceeded, an alarm is set off, signaling a disturbance in the system.

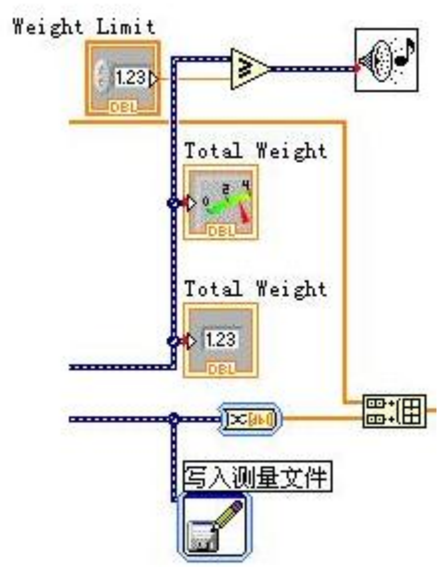

Figure 22: Weight monitoring SubVI (B)

C. The weight limit and total weight data was transferred to subVI (C) below (Figure 23) which computes the data on a set of charts namely the X-mR and X control charts. Data regarding weight was displayed on the man-machine interface pictured in Figure 23.

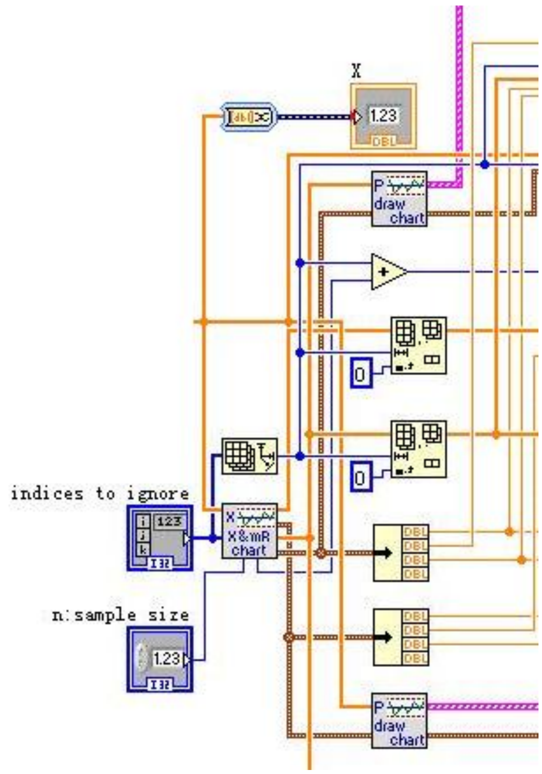

Figure 23: SubVI (C) X-mR and X control charts

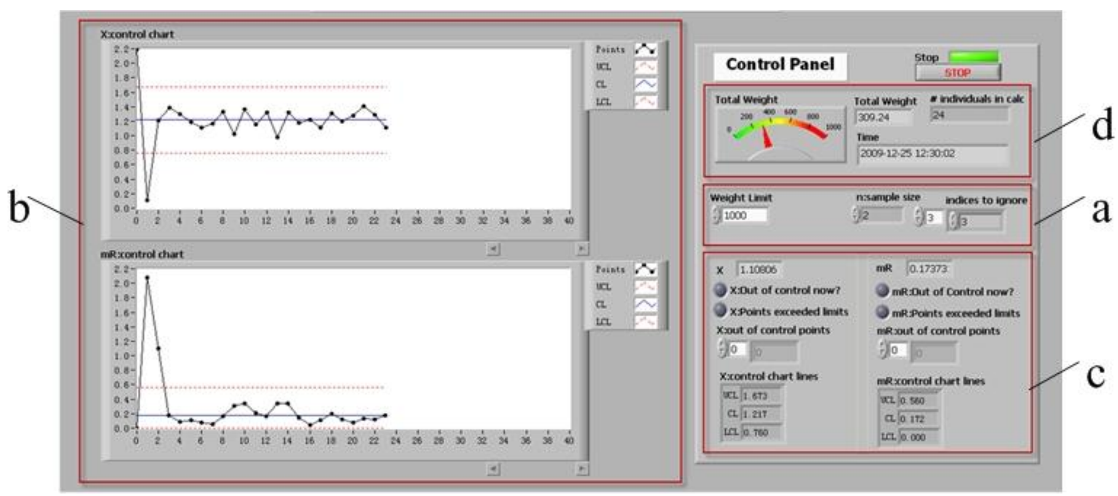

Figure 24: Man-machine interface (15)

a. Parameter input area; b. X-mR control chart display area; c. Display area for monitoring value of Control chart; d. Other functional area.

D. In subVI (D (Figure 25), data displayed on the man-machine interface is monitored and the icons was programmed to set off an alarm when limits were exceeded. If any of the data points exceed the mR and X control chart lines, either upper or lower limit lines, alarms were set off.

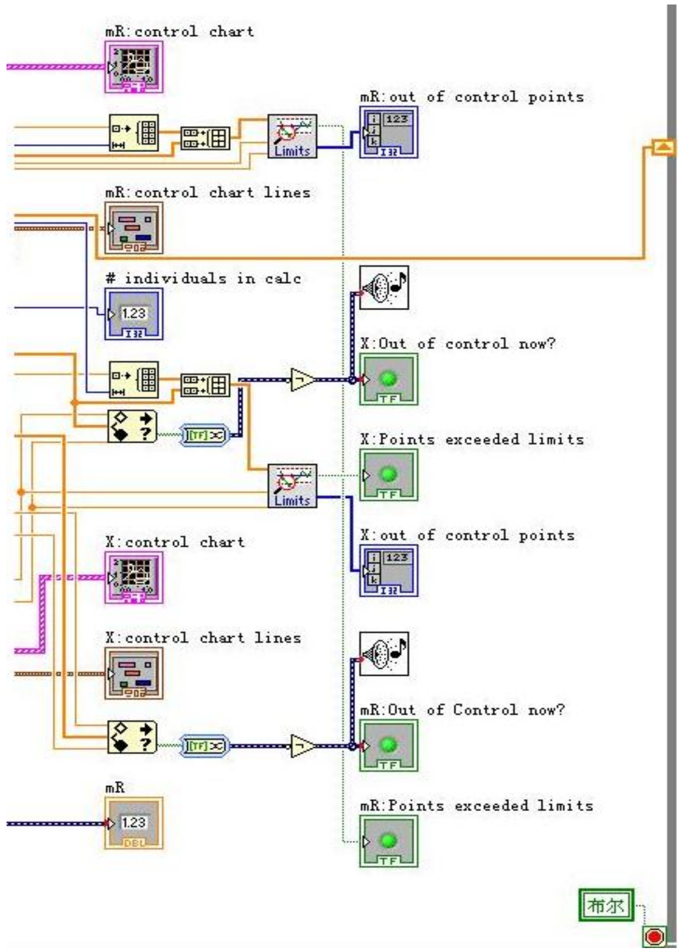

Figure 25: SubVI (D) System control icons

E. To ensure that when disturbances occurred, the entire system was not compromised, Boolean logic was applied to the system. Boolean logic is defined as, "programming that acts as a control in the system and turns the system "on" and "off" when disturbances occur (18).

The use of Boolean logic was to implement a control to ensure quality and efficiency of the mechanical process. Once a limit is exceeded the program would issue a "true flag" which caused the notification to be sent to man-machine interface and an alarm went off. In normal operation, the false flag was set which did not set off the alarm (Figure 26).

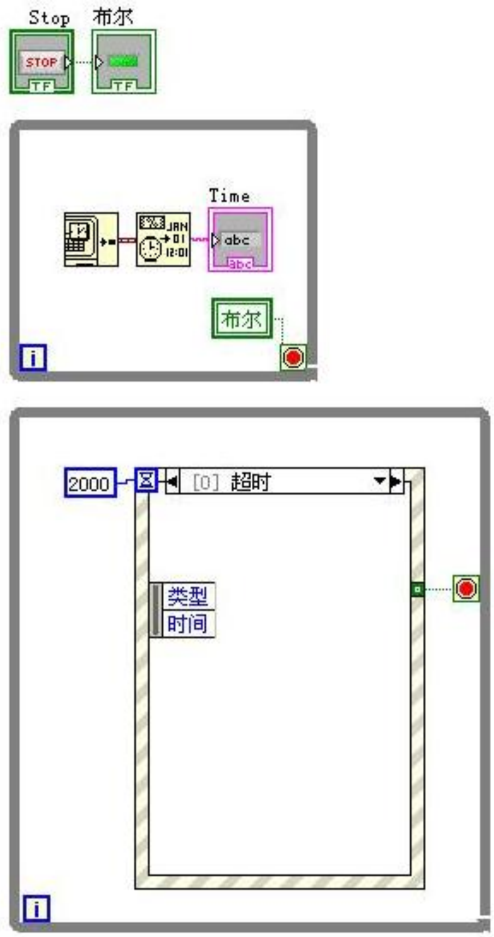

Figure 26: SubVI (E)

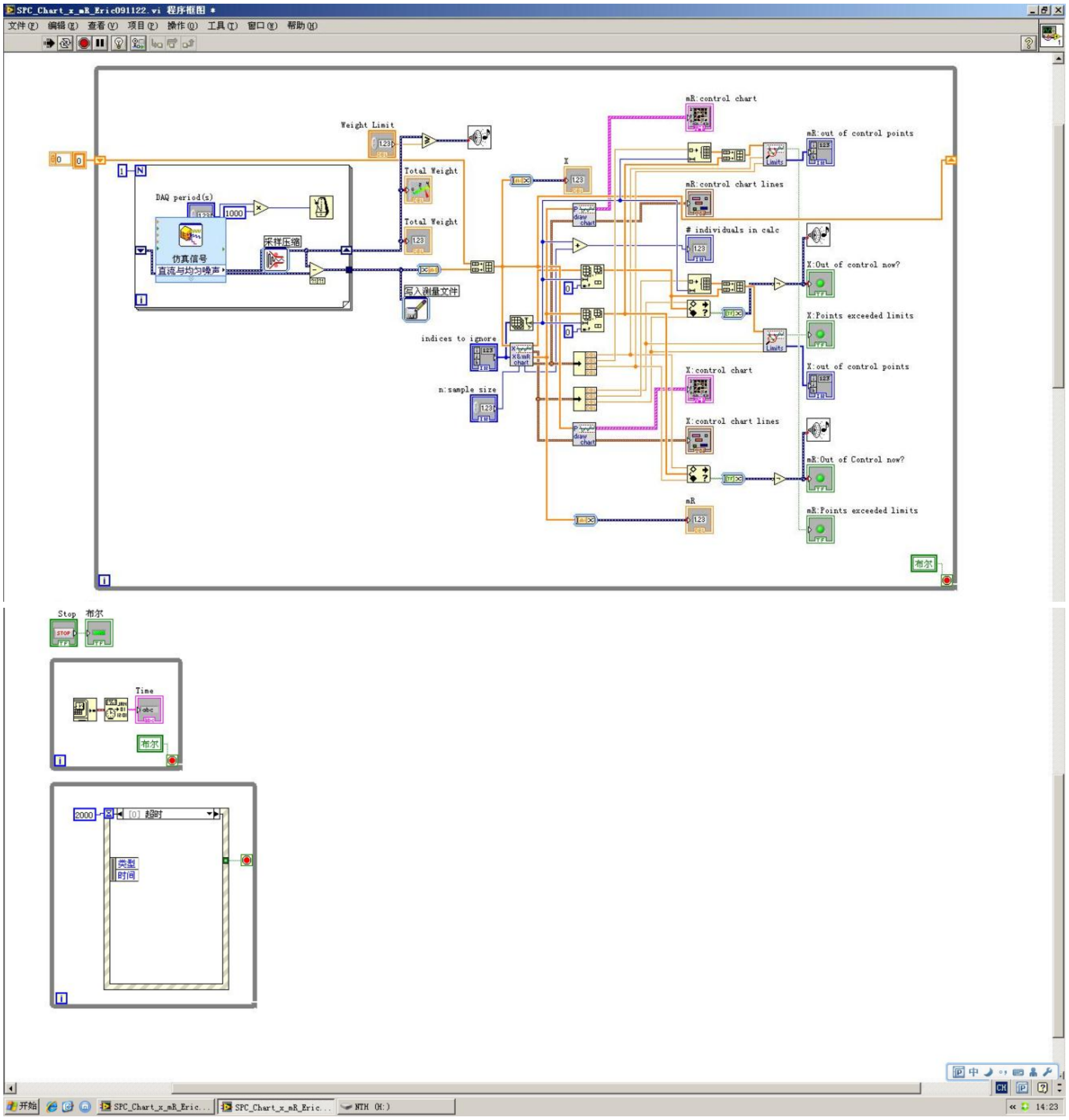

Figure 27: Complete block diagram of monitoring process in LabVIEW program

The X and mR control levels are the limits in which the weight signal from the corona electrostatic separating machine should stay within. These controls levels were displayed on the man machine interface. (See Figure 28).

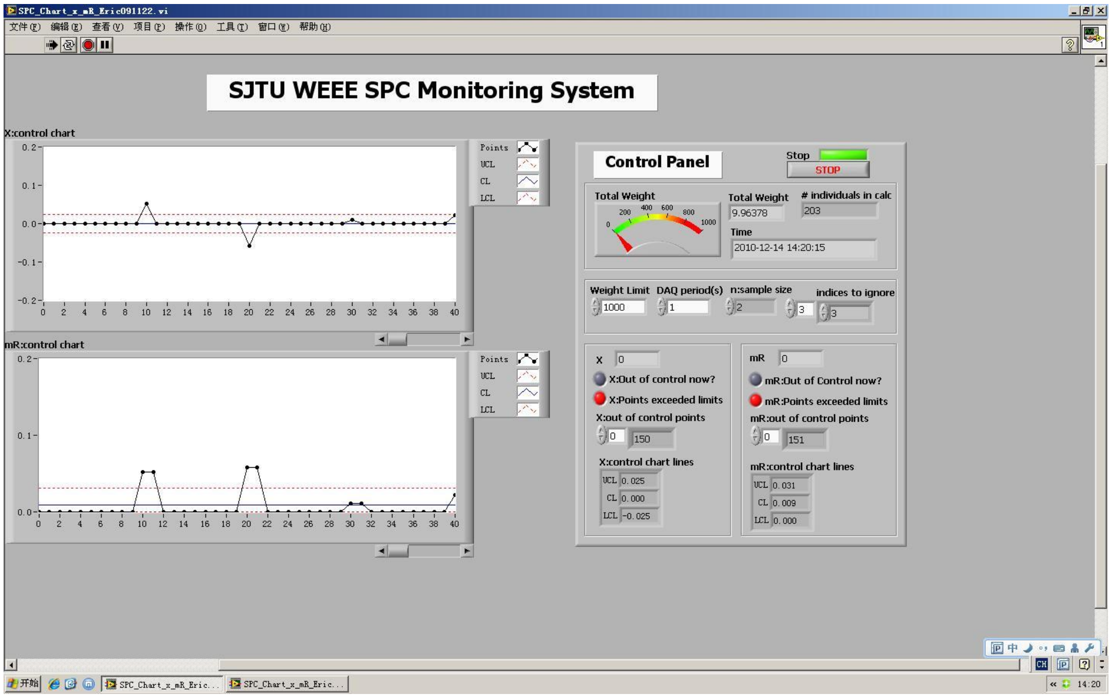

Figure 28: Control chart display using simulated signal

4.2 Improvements on Existing Separation Process

Particle aggregation and high voltage breakdown have been identifies as two notable problems which affect the stability and efficiency of the corona electrostatic separation process (14). Given the opportunity to conduct experiments that will improve the current yields of separation, dealing with the different parameters that affect the separation process and addressing them individually will allow for changes and improvements to be made. The different parameters that can be controlled are particle size, speed of the rotating roll, materials of construction of the rotating roll, shape of the rotating roll, and temperature and pressure in the room the experiments are conducted in. The following discusses approaches to improve the existing corona electrostatic separation process and possible future experiments.

4. 2.1Continuation of Work on Real-time Monitoring System

Had the hardware and software worked and allowed for real-time monitoring experiments to be conducted, we would have been able to move to the next stage of our research which would have been testing three kinds of feed conditions. The three feed conditions are uniform feed, non-uniform feed and electrostatic field breakdown. These feed conditions are the most common feed conditions that have occurred in industry. With this research, the real time monitoring system would be tested for its ability to detect the difference in operation when there is particle aggregation occurring in the system.

4.2.1.1Different Work Conditions

With uniform feed, waste printed circuit board particles of uniform particle size would be fed into the corona electrostatic separating machine. The weight increments would then be displayed on the man-machine interfaces and indicate whether the middling weight accumulation is within the upper and lower control level. With uniform feed, our expectations would be that samples would be within the upper and lower control levels as there would be minimized particle aggregation and so the alarm would not be set off.

The second work condition we would test is the non-uniform feed. This feed consists of a mixture of particle sizes. This feed condition is the most common feed condition that occurs in industrial applications. Li et al. states that, "Because scraped PCBs were mixture particles from large size to small. The fine particles may lead to non-uniform feed, which decrease both the capacity and purity of metal products (19). This would essentially be our most important feed condition to test as it is the most realistic and more relevant to industrial applications. Our expected result would have been that the sample would be displayed on the man-machine interface to be beyond the upper and lower control levels to signify the occurrence of particle aggregation and set off alerts in the form of alarms to be able to notify the operators. From known behavior of particle aggregation witnessed in industry, the nonmetallic particles which aggregate often block the feed inlet (4). This action would decrease the accumulation of the middling on the weight platform, which would be displayed on the man-machine interface as having exceeded the lower control level and hopefully set of an alarm.

The third condition we would test would have been the electrostatic field breakdown. When this phenomena occurs, there is a momentary unwanted current that is created that may cause damage to the equipment or cause electrostatic discharge which would charge the feed particles causing them to aggregate which was mentioned earlier as an unwanted condition in the feed. The momentary unwanted current that is created is due to electrostatic discharge when an electric current flows between two objects which are at different electric potentials. This high-voltage is also very common in industry and is therefore a very important feed condition to test. We would expect the alarm to be set of just like in the non-uniform because the high-voltage breakdown causes uniform feed to become non-uniform feed.

4.3 Particle Size

The printed circuit boards are fed into a grinder which is will crush and grind the boards into tiny pieces. Within this crushing and grinding process, particles of different sizes are formed. The particle sizes range from <0.3 mm, 0.3-0.45mm, 0.6-0.8mm, and 0.8-1.2mm (5). The nature of the grinders cannot be reset to a particular specification so that they only create one type of particle size. Through an extensive amount of research, the particle size ranging from 0.8-1.2mm was identified as the most suitable particle size for effective separation in the corona electronic separating machine (5). This is because smaller particle sizes have a tendency to aggregate. The smaller the particle sizes, the higher the chances of aggregation. While the particles move past each other, an electrostatic charge is created this causes them to become attracted to each other and aggregate. These aggregated particles when fed into the corona electrostatic separation machine either accumulate too much charge or do not get charged enough to remain adhered to the rotating roll until they are released by the brush into the nonmetal bin. They therefore fall into the middling collection box, causing an increase in the weight of the middling collection. This action in turn decreases the effectiveness and efficiency of the corona electrostatic separating process.

A number of steps and changes can be made to the existing corona electrostatic separating process to eliminate the occurrence of aggregation. Focusing on the area before the printed circuit boards are fed into the corona electrostatic separating machine provided an opportunity to try and eliminate as many causes of decreased efficiency.

4.3.1.1 Crushers and Grinders

Further research on the designs of grinders and crushers could be a possible solution to the aggregation phenomena. Particle size has already been identified as a very important parameter that affects the quality and effectiveness of the separating process. A crusher and grinder that can be set to produce particle sizes of between 0.8-1.2mm would eliminate the production of the unwanted smaller particle sizes. This would mean specialized blades would have to be used as well as adjusting the separation between the grinding surfaces as they are the ones that determine the particles size.

Through conducting research, I have identified grinders that are used in the coffee bean grinding industry. Coffee beans of cause have very different physical properties than waste printed circuit boards; however using the basic methods that the grinders use and applying them to the larger industrial grinders may produce desirable results. The burr grinder (seen below in Figure 29) prides itself for having the ability to grind coffee beans to a consistent particle size. Stronger materials for the blades may have to be used as they will be crushing metals and hardened plastics from the waste printed circuit boards which are significantly stronger than coffee beans.

Figure 29: Burr Grinder (20)

The burr grinder has individual settings, allowing the operator to choose the desired particle size, which would be a remarkable breakthrough for our research. There are two types of burr grinders, conical and disk. The conical burrs grinders have been identified as the best grinders as they produce consistent grounds and virtually no static, which would be phenomenal for our research as it will eliminate the problem of aggregation due to electrostatic charge created. There is the disk burr grinder which is, “better than blade grinders, but the very high rotation speed and resulting friction prohibits them from producing as consistent a particle size as the conical grinders” (20).

This conical grinder that is used for coffee bean grinding can be changed to be more suitable for industrial applications. As the feed loads would increase, a grinder that can handle larger capacities will have to be designed. Tests would need to be done to see how the effectiveness and the stability of the grinder changes when its size is increased. This grinder would be able to tackle two areas of concern at the same time, namely non-uniform feed and the electrostatic charge that is created in the corona electrostatic separating machine.

4.3.1.2 Antistatic Control

Another option is to adopt an antistatic devise which is, “Any item which has the effect of reducing static electricity charges on a person's body or equipment, either to prevent fires and explosions when working with flammable liquids and gases, or to prevent damage to static-sensitive objects such as electronic components or devices (21). What this device would be able to do is eliminate all the electrostatic charge created that causes the particles of uniform feed to aggregate due to high voltage breakdown. There are a number of different antistatic devices ranging from bags, garments to agents. A company named Bellex International Corporation has designed antistatic device called the Zerrostat 3®. (See Figure 30).

Figure 30: Zerrostat Antistatic Device (22)

The Zerrostat 3® is effective in neutralizing electrostatic charges. “The pistol-shaped molded plastic device with a trigger mechanism incorporates a unique piezo crystal device. A squeeze of the trigger creates a stream of positive ions and a stream of negative ions on trigger release. This cancels static charges.” (22). Spraying onto the rotating roll surface will neutralize any charges that could have been created before the waste printed circuit board particles are charged by the electrostatic electrode. Another bonus with the Zerrostat 3® technology is that it “prevents charged particles from flying during weighing or transfer of powders and keeps powders from sticking to containers.” (22). Incorporating this pistol device into the corona electrostatic separation technology could aid in eliminating the problem of particle aggregation (Figure 31).

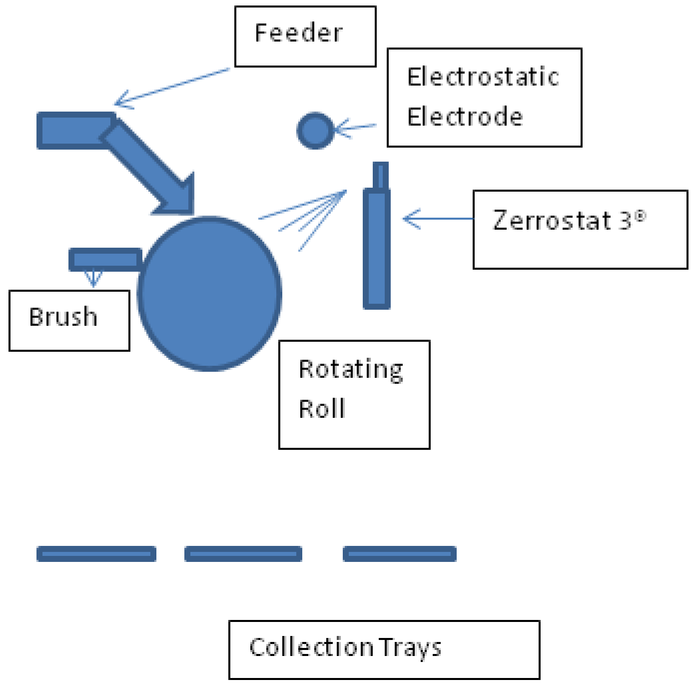

Figure 31: Corona electrostatic separation with static control

4.4 Rotating Roll Speed

The roll-type corona electrostatic separator (RTS) has a rotating roll that spins around as the feed is fed into the machinery. In laboratory settings, testing for the optimum rotating speed which will allow for the most efficient separation will help increase the purity and yield of the separation. Conducting different experiments while varying the speed of the rotating roll and measuring the amount of middling collected will give a good indication as to what the optimum speed is. The speed that produces the least amount of middling will be the most effective speed as that would mean that majority of the material would have been separated into metals and nonmetals. In a laboratory, the scale is very small. In industry, greater output ensures higher profits and so conducting tests on an industrial scale will identify the optimum speed for industrial applications. To produce a greater production capacity in the least amount of time, the roll speed and the feed roll will have to be high. Extremely high speeds may affect the quality and purity of the product and so much care should be taken to avoid jeopardizing the separation quality of the product.

4.5 Shape of the rotating roll

The rotating roll that we used in the laboratory at Jiao Tong University was cylindrical in shape (Figure 32). Different shaped rotating rolls have different diameters and therefore different surface areas. These surface areas mean that the feed would be exposed to the voltage for different amounts of time depending on what shaped rotating roll was being used. Experiments investigating different shaped rotating rolls may bring to light more advantageous shapes which will have greater separation yields. The feed which would ideally exit from the feeder as a thin stream and therefore would either be exposed to the voltage for a longer time in the case of shape C or for a shorter amount of time as in the case of shape B (See Figure 32).

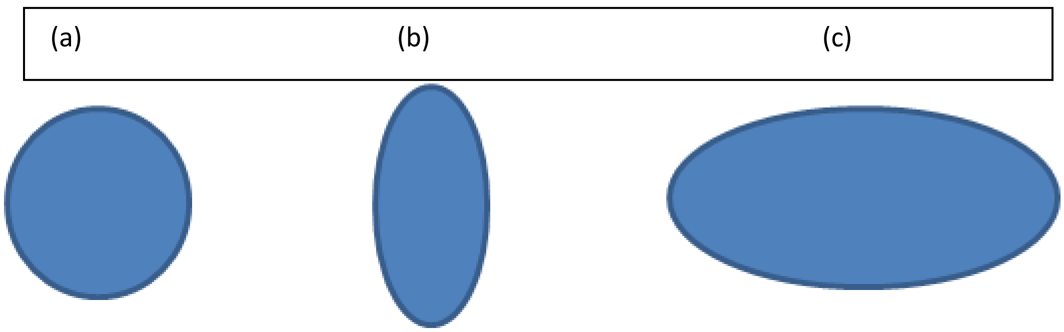

Figure 32: Rotating roll shapes (a) Cylindrical (b) Oval (c) Elongated cylinder

These experiments would also be able to provide information about whether it is advantageous for the feed to be exposed to the voltage for a long or short amount of time. The amount of middling collected will once again be the indicator of the most ideal shape.

4.6 Ambient Conditions

Temperature, pressure and humidity have a great impact on the separation process. Ambient conditions vary significantly in a room or area and as a result may impact the separation process. Controlling these variations may provide information about the most ideal operating pressures and temperatures. It is often extremely difficult to control these conditions on a larger scale and as pressure and temperature controls are expensive. Conducting experiments to establish the difference in yields when these conditions are controlled versus not controlled will give good indicators of whether implementing control units will be a good investment. If the separation yields increase significant when the pressures and temperatures are controlled, it may be in the best interest of the company to invest in control units.

If the separation until does not improve the separation yield to profitable margins, it may not be an area that requires changes.

Table 2: Summary of factors affecting separation and proposed experiments.

Parameters	Experiments
(a)Particle Size	Uniform feed
	Non-uniform feed
	High voltage breakdown
(b) Rotating Roll Speed	Middling accumulation at different roll speeds
(c)Shape of Rotating Roll	Different shaped rotating rolls
(d) Ambient Condition	Stabilizing ambient conditions

Table 2 above indicates the different parameters which can be adjusted in order to improve the existing corona electrostatic separation process. The particle size can be adjusted to test the effectiveness of the LabVIEW program. Conducting experiments using uniform feed, non-uniform feed and high voltage breakdown will test the LabVIEW responses in the form of alerts. This parameter affects the separation process. Conducting experiments testing the speed of the rotating roll speed and changing the shape of the rotating roll will create different experiment condition which when tested will vary the separation yield. Controlling ambient temperatures and identifying which temperatures, pressures and humidity provide the optimal operation conditions will increase the separation yield.

4.0 Conclusions

The alarm successfully went off ruling out the software as the possible cause of the problem. Not only did the simulation serve as a good diagnostic check, it also proved to be a great indicator and exemplifier of what would be displayed on the X and mR- Control chart interfaces if the software and the hardware were connected. When all data points are within the upper and the lower control levels, the system is assumed to be running smoothly.

The alarms sounded off when we ran the simulated signal through the LabVIEW program. This meant that if the software and hardware were connected, and there was either high voltage breakdown or particle aggregation in the separating process that was causing the separation process to malfunction, the alarm would alert the operators that they attend to the problem. Not only does the alarm notify operators, the high voltage that is being fed to the corona electrostatic separation machinery would be reduced to 0. This is a mechanism that will protect the machinery. With no voltage provided to the machinery, the nonmetal particles cannot gain enough charge to remain pinned on the rotating wheel and as a result most of them fall into the middling collection box. This is a control process as well as an intelligent design of the machinery as it is able to detect and problem and perform and action that will stop the problems from occurring.

The proposed experiments above will aid in making steps to improve the existing corona electrostatic separation process. Testing the different feed conditions will allow for adequate testing of the LabVIEW software program. Maintaining uniform particle size through the use of uniform particle grinders is a promising method that might help to improve the separation yield as it will reduce particle aggregation. However, there exist no industrial grinders that can perform this. Incorporating an anti-static devise to discharge the particles may also be a way to reduce particle aggregation. The rotation speed of the rotating roll presents an area of study which may improve the separation yield. Changing the shape of the rotating roll varies the exposure time that the particles experience from the voltage and therefore may also increase the separation yield. Finally, enclosing the equipment is a possible method to minimize the effects of temperature, pressure and humidity.

5.0 Future work and Recommendations

Technical problems with the data connectors prevented us from achieving a complete software solution. Specifically we were unable to make use of real-time data analytical tools to allow us to proactively identify controls that could keep the process running with in our defined capacity controls. This real time analysis would also give us the historical data we could compare against with a controlled input. This data can be used to identify key areas of low efficiency or low output. Also it could show us where the process is performing at expected or better than expected rates. I recommend a tool that will help identify preset conditions, and quickly notify when they are violated.

Scalability is a major area of concern; the process expands complexity when the capacity is increased. We were unable to accurately identify the effective rate of the process, due to software concerns. However to bring this solution to the industry, the effective rate must be identified to accurately design solutions for customers. I recommend exploring how complex the solution will be at its largest customer request. Also, the solution should be tested on the smallest or micro level where you may be able to create more dynamic solutions for various size clients.

A larger capacity will not only add to the number of rollers but also the efficiency of the components used to do the sorting. At higher speeds and increased capacity the quality of product maybe be degraded. Only executing at large capacities will show exactly how much. I recommend that the team increase the amount of load to accurately identify points of peak performance and over use.

6.0 References

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7.0 Appendix A: Annotated Bibliography

(1) Recycle Technology for Recovering Resources and Products from Waste Printed Circuit Boards

Very Good Source. This article explored the different technologies that had been used to recover resources and products from waste printed circuit boards. Information on the technologies showed the progress and the speed at which changes were being made to the processes used to recover products from waste printed circuit boards.

(2) http://www.webopedia.com/TERM/P/printed_circuit_board.html

Good source. Provided an informative definition to the term printed circuit board.

(3**) Electrostatic Separation for Recovering Metals and Nonmetals from Waste Printed Circuit Board: Problems and Improvements**

Very Good Source. This article presented existing problems with the recovery processes and aimed to investigate and improve those problem areas. This article gave me an understanding of the improvements that the electrostatic separator still needed at this time. It paved the way for greater discoveries and means of improving existing operation methods.

(4) **Environmental Friendly Automatic Line for Recovering Metal from Waste Printed Circuit Boards**

Very good source. This article exams and introduces the use of the automatic line which is an industrialization technology that is low in cost and pollution emission. This article provides very good illustrations of the equipment and output of materials looks like. I was able to get a deep understanding of how the process of recovering precious metals from the descriptive illustrations.

(5) **Optimizing the operating parameters of corona electrostatic separation for recycling waste scraped printed circuit boards by computer simulation of electric field**

Very good source. This article studied the parameters that allowed for optimum operation of corona electrostatic separation for recycling waste scraped printed circuit boards by computer simulation of an electric field. I study continued from the introduction of the computer simulation and so it provided information about how the simulations could be used to improve separation.

(6) **A Model for computing the trajectories of the conducting particles from waste printed circuit boards in corona electrostatic separators**

Good source. This article gave me an understanding of how trajectories can be studied to increase the efficiency of the separation. At first glance, one my not think that the angles at which the particles are released will have any importance but this article makes you realize how important these angles are. The computer software (MATLAB) allows these trajectories to be studied and computed which aid in the study.

(7) **Application of corona discharge and electrostatic force to separate metals and nonmetals from crushed particles of waste printed circuit boards**

Very Good Source. This article provided a very brief but informative background to the problems caused by increase demand for technology. Corona electro static separation was also introduced and the methods that needed to take place for adequate separation. The article mention density and electrical conductivity of the metallic and nonmetallic samples as being important its applications to be separated. The pre-processing stage was introduced which aided in effective separation with particle size as its main concern.

(8) **Phenolic molding compound filled with nonmetals of waste PCBs**

Very Good Source. This article outlines the use of nonmetals. Specifically in the Phenol molding compound process where the nonmetals are used as fillers. This article provided great insight to what the nonmetals could be used for as they are the major by product in the corona electrostatic separation process.

(9) **Optimal high-voltage energization of corona-electrostatic separators**

Very Good Source. This article gave me an in-depth analysis and understanding of the optimal high voltage energization for corona electrostatic separation. I got to understand how the charging of the particle occurs as well as how their different properties contribute to the difference in the ways in which they act.

(10) Li, J., Xu, Z.M., Zhou, Y.H., "Theoretic model and computer simulation of separating mixture metal particles from waste printed circuit board by electrostatic separator", Journal of Hazardous Materials, 2008, 153, pp. 1308-1313

Very Good Source. The roll-type electrostatic separator (RES) to recovery low content metals in waste PCB was introduced. This method presented an improved method of recovering precious metals. A deeper understanding was also provided regarding the use of MATLAB and its use to simulate the models.

(11) **A Novel Process for Recovering Valuable Metals from Waste Nickel-Cadmium Batteries**

Good Source. With focus on waste nickel-cadmium, the impact of one pollutant was greatly studies. This allowed the reader of the article to view the damage only one type of waste can do. This gave me a deeper understanding of the need and urgency of ways to recover and treat these waste materials.

(12) **Critical Rotational Speed Model of the Rotating Roll Electrode in Corona Electrostatic Separation for recycling waste printed circuit boards**

Very Good Source. This article exams a small but very important parameter, the rotational speed. The rotational speed was examined to provide the maximum and optimum rotation speed that would offer the best separation experiment and purity.