Automating Low-Level Nuclear Waste Sorting: Enhancing Efficiency, Safety, and Scalability in Laurentis Energy Partners Facilities

Automating Low-Level Nuclear Waste Sorting: Enhancing Efficiency, Safety, and Scalability in Laurentis Energy Partners Facilities

By

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Lay Abstract

The goal of developing a Low-Level-Waste (LLW) automation apparatus is to help enhance Laurentis Energy Partner's (LEP) LLW current manual sorting process. Currently more than 90% of the worlds nuclear waste produced or stored waste is classified as low-level waste (LLW) (*Radioactive Waste Management - World Nuclear Association*, n.d.-a). Currently at LEPs LLW classification is a manual process accomplished by workers. Automation of LLW classification reduces the amount radiation workers are exposed to, ensures accurate and standardized radiation measurements, and improves processing efficiency. The apparatus automates key tasks such as weighing waste bags, gamma radiation measurements, and tritium measurements are automated reducing the overall number of workers required down from four to one. Currently between manual processing and automated processing there is not a significant time saving, but future upgrades can potentially boost productivity by up to 95%. The modular design aspect allows for easy expansions and helps prepare LEP for handling higher emission waste while improving safety and efficiency. Adding automation to LEP will place them ahead for nuclear waste management solutions, obtaining long-term safety and sustainability.

Abstract

Objective: Automation is used in numerous industries; waste management is one example. In this work we design a LLW Automation to improve LEPs process. The goal is to reduce the amount of radiation workers are exposed to, improving the consistency of radiation measurements, and improving the overall efficiency of LLW processing. Worldwide, LLW accounts for over 90% of nuclear waste produced from hospital, industries and nuclear fuel cycle. LLW includes various contaminated items requiring delicate handling. *Methods:* The apparatus automates three key aspects of the process, **weighing the bags, performing 360° gamma radiation measurements, and tritium measurements.** Workers involved in the sorting process has been reduced by a factor of 4. Allowing a single worker to operating one or multiple apparatuses simultaneously. The apparatus ensures a standardized method of measuring is applied to every bag passing through LEPs sorting facility eliminating inconsistencies introduced with human intervention. Finally, the apparatus features a modular design, enabling future expansions with new detectors. *Conclusion:* The apparatus is successfully able to reduce the workers needed for LEPs process by 75% transitioning from 4 workers to 1. While the apparatus may not provide meaningful time savings in its current state, projections with automation ready detectors and parts can improve productivity by 75% (1 unit), and up to 95% (5 unit). It provides significant times savings for LEP through standardized gamma and tritium measurements thus reducing human error and optimizing processing using less workers. *Significance:* The automation not only improves LEP's process, but also prepares LEP's facilities for higher radiation handling capacity and volumes. The modular design enables expansion and scaling. It allows new

technologies and capabilities to be introduced later. Finally, this device improves the efficiency and safety of nuclear waste management through automation.

Acknowledgements

I would like to sincerely thank my two supervisors, Dr. Tom Wanyama, and Dr. Nagasaki for their guidance and help throughout this journey. Undertaking this research could not have been possible without their help of them. There were times when I struggled making connections between Nuclear Engineering and Automation Engineering, with the aid of their help I was able make appropriate connections between the two disciplines. Dr. Wanyama's expertise in Automation Engineering helped me seek out methodologies that I can use to fulfill my goals which I had not known before such as PLCs. Dr. Nagasaki's guidance on nuclear radiation techniques, and how to make better measurements helped me dive future into radiation detectors and their implementation in automation.

I would like to extend my heartfelt thanks to the staff at Laurentis Energy Partners for allowing me to showcase the incredible work they do in sorting Low-Level Nuclear Waste at their Hamilton Facility. They provided essential training on effectively measuring gamma and tritium radiation. Lastly, I am grateful for the opportunity to shadow LEP employees to gain firsthand insight for their process and develop the LLW sorting Apparatus.

Would like to appreciate the time Derek Cappon, and the folk at the Bot Engineering team for helping me set up a meeting with them to select the optimal gamma detector with serial output for my research. Would like to sincerely thank Derek Cappon for allowing me to use the Health Physics Radiation Lab to test gamma detectors out for my research.

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Abbreviations

Abbreviation	Full Form
AD/DA	Analog-to-Digital/Digital-to-Analog converter
BLE	Bluetooth Low Energy
BMR	Bin Measurement Room
FOAK	First of A Kind
GM	Geiger-Muller
HMI	Human Machine Interface
I2C	Inter-Integrated Circuit
ILLW	Intermediate Low-Level Waste
LEP	Laurentis Energy Partners
LLW	Low Level Waste
LoRa	Long Range
MQTT	Message Queuing Telemetry Transport
mSv	Millisievert (unit of radiation dose)
OPG	Ontario Power Generation
PLC	Programmable Logic Convertor
SPI	Serial Peripheral Interface
UART	Universal Asynchronous Receiver-Transmitter
USB	Universal Serial Bus
VLLW	Very Low-Level Waste
µrem	Microrem (unit of radiation dose)

Contents

Chapter 1.0: Introduction

Canada's participation in the Paris agreement (Government of Canada, 2021) to reduce Canada's carbon emissions requires that we have a robust energy source that can not only provide the necessary energy requirements but ensure the future population growth's energy demand will be met, respectively.

Nuclear energy is classified as a low-carbon emission energy source (Nuclear Power and Climate Change, 2016). The vector error correction model indicates that nuclear energy can help reduce emissions in the long run (Saidi & Omri, 2020). Nuclear reactors produce energy during all times and environmental conditions, which grants them the highest capacity factor. The capacity factor indicates the percentage spent producing power in a year. Nuclear energy has a capacity factor of 92.5% (Nuclear Power Is the Most Reliable Energy Source and It's Not Even Close, n.d.). While nuclear reactors do not produce greenhouse emissions, they do produce nuclear waste. It is critical that nuclear waste is handled and disposed of correctly. If not, it can potentially cause environmental contamination.

There are a few ongoing programs referred to as deep geological repositories intended to store depleted fuel, but nothing significant for sorting LLW. Nuclear waste is a broad term that is split into multiple categories, which will be investigated in later sections. One type of waste that is of interest is Low Level Nuclear Waste, which accounts for over 90% of the total waste produced from the operation of hospitals, industries, and nuclear fuel cycles (Radioactive Waste Management - World Nuclear Association, n.d.-a).

Laurentis Energy Partners is currently one of the only companies in Ontario that is actively involved in sorting LLW. Their approach relies on manual sorting, similar to how conventional garbage is sorted, but with the added risks associated with radioactive materials. Automation with the addition of Industry 4.0 techniques is highly valuable in this scenario and is needed to ensure that LEP can sort the waste at a rate quicker than is produced.

In the journal Robotics and Artificial Intelligence in the Nuclear Industry: From Teleoperation to Cyber Physical Systems," autonomous systems are a key application of Industry 4.0 in nuclear decommissioning (Shanahan et al., 2023). These systems can automate tasks such as radiation monitoring, waste manipulation, and mapping, making it possible to operate in high-radiation environments with minimal human intervention. This is an example of Industry 4.0 techniques being used to transform nuclear waste management, improving both safety and operational efficiency.

Additionally, there are several companies that employ automation, but not for this specific application. Berkshire Grey is one company that provides an automation system for warehouses, allowing sorting of items waiting to be shipped to customers and for items that have been returned (*Warehouse Automation Sortation System - Berkshire Grey*, 2022). Secondly, Plus One Robotics is another example of companies that incorporate automation for sorting items. They provide solutions for small package sorting. They have deployed their automated small package sorting at FedEx (*FedEx Small Package Sorting Automation Expansion | Case Studies| Plus One Robotics*, n.d.). Lastly, Eclipse Automation provides automation solutions not necessarily for waste management but for refurbishment and decommissioning of nuclear facilities (*Nuclear*

Industry Automation Solutions, n.d.). These are some examples of the role automation plays in nuclear and general sorting.

While automation has found diverse applications in industries such as warehousing, logistics, and nuclear facility management, its potential for improving nuclear waste sorting remains largely undiscovered. This presents a significant opportunity to explore how automation can be specifically applied to streamline the handling and processing of nuclear waste, which involves different tiers of radiation classification. Now that we have an introduction about nuclear energy and nuclear waste, the next section will discuss the motivation behind the thesis.

1.1 Motivation

Nuclear waste is broad term. It encompasses different tiers of radiation based on the emissions the object gives off. There are 4 types of categories that nuclear waste can be segregated into, and it depends on the emissions that are given off from the item and is determined by a government organization.

Table 1 Distribution of Nuclear Waste's and their Allocated Storage

Type of Waste	Allocated Storage
Very Low-Level Waste	$2{,}356{,}000\ \mathrm{m}^3$
Low Level Waste	$3{,}479{,}000\ \mathrm{m}^3$
Intermediate Level Waste	$460{,}000\ \mathrm{m}^3$
High Level Waste	$22{,}000\ \mathrm{m}^3$

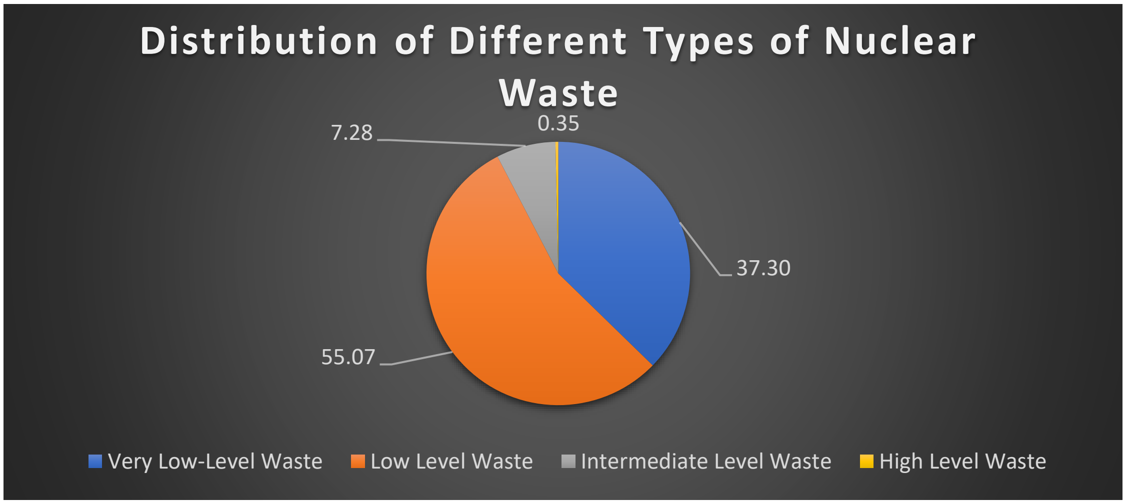

Figure 1 A Visual Representation of the different types of nuclear waste in percentage (Radioactive Waste Management - World Nuclear Association, n.d.-b)

Figure 1 illustrates that LLW and VLLW combined account for 92% of stored nuclear waste. Now to make matters worse, VLLW and LLW are highly variable in size and material of the objects. These two categories of waste typically include items such as tools, scrubs, wires, and anything that may be used in a power plant near radiation that has the potential to be classified as VLLW and LLW. This makes it difficult when it comes time to sorting. LEP in Hamilton receives this waste from Ontario Power Generation in metal bins, the bins contain bags which themselves contain the waste. Given the volume of LLW nuclear waste, manual waste sorting is prone to errors, and increased radiation exposure to workers. Automation provides a method of mitigating these issues using Industry 4.0 methodologies.

1.2 Thesis Overview

This thesis describes the development of LLW measurement apparatus for Laurentis Energy Partners (LEP) in Hamilton, Ontario. LEP is an Ontario Power Generation subsidiary company, specializing in nuclear energy solutions. The primary focus of LEP is clean energy technologies and aiding in advancing nuclear energy. They specialize in the following areas: LEP produces medical isotopes for application in cancer research and sterilization. Cobalt-60 is one isotope produced by LEP. Its applications include, inspecting materials to visualize internal structures, flaws, or foreign objects, and sterilizing foods. In the medical field, cobalt-60 is used to treat certain types of cancer and to sterilize medical equipment (*Cobalt-60 | Uses & Radiation | Britannica*, n.d.). LEP is heavily involved in developing and supporting small modular reactors (SMRs) and taking on refurbishments of nuclear facilities globally. The most recent development is in Romania, where LEP secured a €3.156 million to support the refurbishment of Romania's Cernavoda CANDU Reactor (*Laurentis Energy Partners Wins Contract in Romanian CANDU Refurbishment » Laurentis Energy Partners*, n.d.). Laurentis Energy Partners (LEP) provides services for nuclear facilities, including maintenance, inspections, and providing waste management services for nuclear plants (*Nuclear Lifecycle Services » Laurentis Energy Partners*, n.d.). Lastly, LEP provides waste management services for LLW, including segregation services and, volume reduction of byproducts using incinerable, compactable, metal, washable, and non-processable materials. This allows LEP to help their clients decrease the amount of nuclear waste material stored at their sites, resulting in reduced operational costs (Waste Management » Laurentis Energy Partners, n.d.). This area of LEPs work is of interest for this thesis. LEP processes and sorts of low-level nuclear waste provided by its parent company, Ontario Power Generation (OPG). Figure 2 outlines LEP's process, from the arrival of waste bins to bin checks, measurements, sorting, and shipping out the sorted waste. LEP holds a license allowing them to handle radioactive material at intermediate levels, with a possession limit of $2.5\ \mathrm{Ci}$ or $9.25 \times 10^{1}\ \mathrm{GBq}$. This limit prevents them from handling waste with emissions above a specified level. Currently, all sorting, measurement, and documentation of radiation levels are done manually.

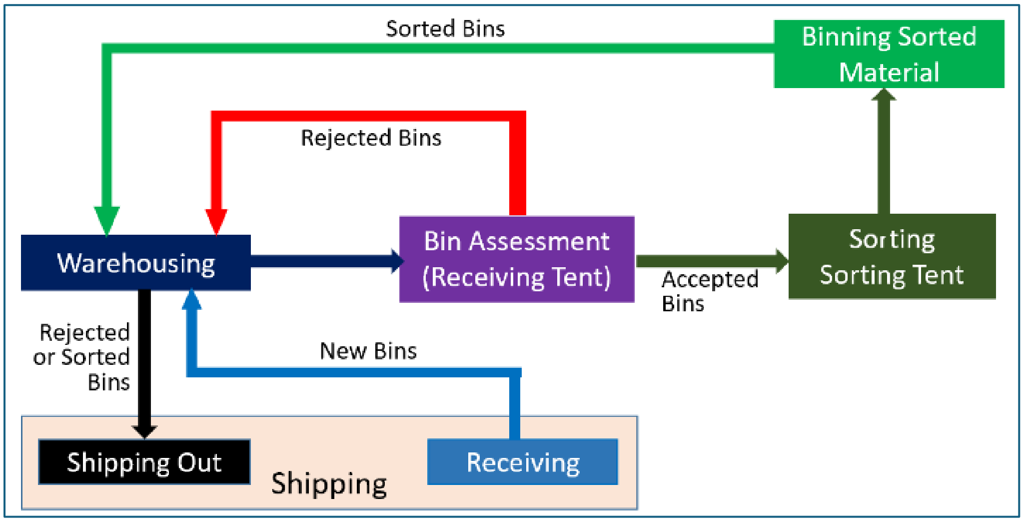

Figure 2 Flow of Bins Through the Main Activity Categories of the Lab

To improve this manual process, LEP contracted TechBasics to perform a time and motion study to assess the time needed for various activities in their LLW sorting process. Tech Basics is a company that specializes in industrial automation and technology solutions. Their services include training programs for PLC programming and Industry 4.0 applications specifically industrial automation integration and artificial intelligence. They also offer system integration and consulting services with a focus on automating and improving industrial processes using modern technologies such as IOT.

As a result, Techbasics did a deep analysis of the LEPs process from the waste arriving at the facility to the waste leaving the facility to determine the effectiveness of their process. Tech Basics provided a detailed list of all the bottlenecks present in LEPs.

Techbasics identified that the Bin Assessment stage introduces a significant bottleneck. Assuming a bin is considered processible, accessing and assessing the bags inside takes several minutes. This introduces delays and further slows down the subsequent step. From the study TechBasics has made 10 recommendations to improve the process. One of the recommendations is automating data entry to streamline operations, including tasks such as scanning bins for gamma emissions, measuring tritium levels in bags, detecting loose emissions, and monitoring fume hoods and background emissions.

Based on findings from TechBasics, automation can help LEP reduce the number of personnel exposed to radiation and improve the accuracy of data collection. The apparatus designed for this purpose serves as a demonstration of the potential improvement's automation could bring to LEP's sorting procedure in the BMR. However, logistical challenges have prevented the apparatus from being tested within a radioactive environment. The apparatuses size and delicacy deemed it difficult to transport to test at LEP's facility. Instead, projections suggest that the apparatus would be effective. While it does not address all of TechBasics recommendations, it provides a foundation for future expansions to fully automate the sorting process.

1.3 Thesis Breakdown

The thesis is structured into five chapters: Introduction, Background, Low-Level Waste Measurement Automation Apparatus Design, Results, and Conclusion and Discussions. Each chapter expands on the Introduction by exploring LEP waste processing and the necessary equipment for LLW sorting. The Background chapter covers nuclear waste classifications, the importance of automation, and relevant engineering concepts. This foundation supports the design of the LLW measurement apparatus, with subsequent chapters addressing development outcomes, anticipated impacts, and future advancements, concluding with broader implications for nuclear waste management. Here is a detailed breakdown of the contents of each chapter.

Chapter 2.0 provides background information and insight on the criticality of having automation involved in LLW sorting. The chapter goes over the different types of nuclear waste classifications. Chapter 2.0 indicates the amount of waste that has been accumulated till now and the rate of growth for the respective waste classification. The chapter contains a brief introduction to what automation is, specifically speaking, Industry 4.0, and the techniques that can be associated with it. There is a brief introduction to the wireless and wired communication methods that can be used to communicate between sensors and their respective controllers. A brief overview of detectors used by LEP and other detectors that were investigated is included. A deeper review of gamma detectors is provided, as well as radiation exposure limits from LEP.

Chapter 3.0 discusses the design and implementation of the LLW measurement apparatus and describes design choices. It starts with the opening statement describing the problem that is being solved, providing a summary of what the current solution is and the necessary background information. It then dives into the system design at a high level, then goes into detail for each of the components in the electrical and software aspects of the system. This is then followed by the specific reasons as to why certain design choices are made. Chapter 3.0 includes the engineering aspect of the system.

Chapter 4.0 discusses the results that are obtained and projections that can be made based on data collected during development and testing of the apparatus. This section is critical as, due to the nature of the work, it was unable to be tested in a radioactive area due to logistic reasons. It provides projections on how the LEPs process can be improved with the apparatus added and the changes that it brings.

Chapter 5.0 provides a conclusion about the implementation of automation in the LEPs process, and aspects that could have been done differently, improvements that could be made to the existing apparatus, and areas of the LEPs process that can be added to the automation. It also provides insight into how this automation fits into the grand scheme of nuclear waste management and what it can potentially become in the future.

This brings the thesis breakdown to a close and provides a broad overview of the information covered in each chapter.

Chapter 2.0: Background

The background section provides a comprehensive overview of theo material needed to understand the motive behind the thesis mentioned in the introduction. This section will explore the categorization of nuclear waste, the types of radiation emitted, and the role of automation in improving nuclear waste management processes, particularly in the low-level waste (LLW) sorting at Laurentis Energy Partners (LEP). By understanding the technical components and methodologies, we lay the groundwork for implementing a safer and more efficient LLW automated measurement system.

2.1 Energy Crisis

The journal "The 21st century population-energy-climate nexus" (Jones & Warner, 2016) highlights a key point: projections indicate that the world's population will reach 10.9 billion by 2100. Currently, a fifth of the world's population does not have access to electricity. Additionally, to obtain the target of limiting global warming to $< 2°C$, significant use of renewables is required.

2.1.1 Renewable Energy Sources

There are several different renewable energy sources that can be used to obtain this target. Solar, wind, geothermal, biomass, and hydroelectric energy are a few renewable energy sources that can be utilized to hit the target of reducing global warming. However, each of the sources has its individual advantages and disadvantages.

Solar energy is readily available in most parts of the world, is cheap to implement, and can be used for commercial or industrial purposes. The downsides are that it occupies a vast amount of land, resulting in low density (with respect to $\frac{\mathrm{kWhr}}{\mathrm{km}^2}$), and energy is only produced while the sunlight is (*Pros and Cons of Solar Panels | Find out Today!*, 2023). Surplus energy produced by solar panels needs to be stored using batteries for it to be utilized at a later point in the day when the panels are unable to generate electricity, adding additional cost and complexity. These are the advantages and disadvantages associated with solar energy.

Wind energy can be deployed as separate wind turbines or as a part of a large wind turbine farm. It has a low operating cost and produces no emissions. The downside to wind energy is that it is weather dependent, indicating that it will produce energy when there is an optimal amount of wind. If it is too windy or there is not enough wind, there is no energy production. Wind energy does not produce a physical byproduct but causes disturbances to the surrounding wildlife, especially birds (Kumara et al., 2022). The Government of Canada conducted a study to understand the impacts of wind turbine noise and the implications on health. They concluded that there is a direct correlation between noise produced by wind turbines and increased annoyance within the community (Canada, 2012). These are the advantages and disadvantages associated with wind energy.

Geothermal energy is a reliable source of clean, emission-free energy. It requires a small footprint on land while providing high energy density (with respect to $\frac{\mathrm{kWhr}}{\mathrm{km}^2}$). The downside of geothermal energy is that it is region specific and can only be implemented in specific regions, allowing access to geothermal vents. The initial cost of building a geothermal station is high, and can potentially trigger seismic activities in the area (*Environmental Impacts of Geothermal Energy | Union of Concerned Scientists*, n.d.). These are the advantages and disadvantages associated with geothermal energy.

Biomass energy utilizes waste products that would have gone to landfills for energy. The downside to biomass energy is that it is still classified as carbon emission-emitting but less compared to fossil fuels. Biomass energy can also potentially compete with food production for land and resources. Lastly, it also produces a byproduct known as fly ash (Odzijewicz et al., 2022), which is a key ingredient in concrete. These are the advantages and disadvantages associated with biomass energy.

Hydroelectric energy produces reliable, emission-free energy. The biggest downside to hydroelectric energy is the requirement of large dams requiring vast amounts of land to create reservoirs. Building large dams and their respective reservoirs may involve the relocating of communities residing in the area and significantly impact wildlife. There is no significant hazardous waste produced during the production of energy from hydroelectric dams. These are the advantages and disadvantages of hydroelectric energy.

As we see above, similarly to fossil fuel-based energy sources, renewables have their respective downsides, making it difficult to be applied in every demographic and climate each country entails. There is a source that, while being a non-carbon emitting source, can be used: nuclear energy. However, nuclear energy has a bad perception in the public due to the radioactive waste produced by nuclear energy. A paper published about the people's perception of nuclear engineering (*Advantages and Disadvantages of Nuclear Energy in Turkey_ Public Perception[#344719]-360884.Pdf*, n.d.) indicates the advantages and disadvantages of nuclear engineering.

Starting off with the advantages, which include a reduction of energy dependence. Nuclear reactors allow significantly reducing the reliance of oil and natural gas. The environmental benefits are that there are no greenhouse gas emissions as a byproduct, making it a great candidate for combating climate change. Lastly, nuclear reactors are not linked with external factors preventing energy production, such as time of day, wind speed.

The downsides to nuclear energy are their initial costs. First-of-A-Kind (FOAK) reactors are significantly more expensive than other methods of energy production. There is always a risk of catastrophic events like Fukushima or Chernobyl. Lastly, waste produced from a nuclear reactor is presented in two forms: depleted fuel from the production of energy and waste produced because of being in close proximity to the fuel during operation. The focus for this thesis is the waste produced as a result of being in close proximity to a radiation source, such as nuclear fuel.

2.1.2 Applications of Nuclear Energy

There are other applications of nuclear energy in the marine industry. For instance, aircraft carriers and nuclear submarines are prime examples of nuclear. There is a slow transition of nuclear energy being applied to regular cargo ships, which currently travel intercontinental routes. Transitioning to nuclear energy helps reduce carbon emission (Issa et al., 2022). Nuclear reactors that are utilized in energy production also have other applications, such as the fabrication of specific isotopes that can be used for cancer research. (Morreale et al., 2012) purposes the production of molybdenum-99 for nuclear medicine using CANDU reactors. This application is unique to nuclear energy and cannot be done with other sources of energy production.

2.1.3 Future of Nuclear Energy

Lastly while the energy production will continue to be diversified between renewables and nuclear energy, more nuclear power plants are to become active in the future, as of 2023, there are 64 new reactors spread across 15 countries which are under construction. Additionally 20 new countries are developing nuclear policies to build their first nuclear reactors (*NEW REPORT HIGHLIGHTS INCREASE IN GLOBAL NUCLEAR REACTOR GENERATION & PERFORMANCE - World Nuclear Association*, n.d.). As more reactors get built and begin operation, this will produce more nuclear waste, which will need to be eventually managed alongside the current accumulated waste.

2.2 Nuclear Waste Categorization

As new reactors enter development and eventually transition into operation, additional nuclear waste will be produced, further needing facilities that can adequately dispose of the nuclear waste. It is critical to understand the different categories of nuclear waste. Understanding the type of nuclear waste can help tailor the automation to specific needs.

Spent fuel is not the only type of nuclear waste produced from the operation of a nuclear power plant. There are four main types of categories as shown in

Figure 1 A Visual Representation of the different types of nuclear waste in percentage (Radioactive Waste Management - World Nuclear Association, n.d.-b)

, where it is evident that LLW (Very Low and Low combined) accounts for over 90% of the total nuclear waste produced. As a result of the shear volume and the variability in the composition of LLW, it is the primary focus for automation. Nuclear waste is categorized into 4 main sections: Very Low Level Waste (VLLW), Low Level Waste (LLW), Intermediate Level Waste (ILW), and lastly High Level Waste (HLW).

VLLW is not considered harmful to people or the environment as it mainly consists of demolished materials which include bricks, concrete, plaster, metal, valves, piping, and other construction material that may come from the decommissioning of a plant or a fuel reprocessing facility.

Low level waste is classified as waste that may at most have an emission of $4\frac{GBq}{t}$ of α radiation or $12\frac{\mathrm{GBq}}{\mathrm{t}}$ of β radiation. LLW waste units are provided in GBq as it does not generate significant heat. The Canadian Nuclear Safety Commission (CNSC) definition of LLW is materials that contain radionuclide content above established unconditional clearance levels and exemption quantities, but generally has limited amounts of long-lived radionuclides. LLW requires isolation and containment for period that can be up two a few hundred years and is suitable for near surface disposal. LLW does not require shielding when handling or while being transported. Low level waste can be processed in surface level facilities and does not have to be stored or processed underground. This waste is typically produced from the industry during fuel fabrication, reactor operation, and hospitals. It consists of tools, filters, papers, rags, clothing, and more. Statistically, LLW accounts for 90% of the overall nuclear waste produced but is only 1% of the total radioactivity

ILW is considered more radioactive as it can produce a decay heat $\leq 2\frac{kW}{m^3}$. Decay heat is the energy/ heat released as a direct result of the material decaying, typically known as alpha, beta or gamma radiation (excluding neutrons). Decay heat can cause the material to heat up, but the levels indicated for ILW are not significant. ILW requires some shielding while handling, but since the heat levels are considered low, it is not necessary to select the method of storage and disposal based on the heat. Items that are categorized as ILW include resins, chemical sludges, and metal fuel cladding. This also incorporates materials that were removed during reactor decommissioning. Small ILW items can be put into concrete or bitumen and solidified for disposal and storage. All together, ILW accounts for 7% of all the nuclear waste produced but accounts for 4% of all the radioactivity from nuclear waste.

HLW produces a heat of $\geq 2\frac{kW}{m^3}$. When handling or transporting HLW, shielding and cooling are required. HLW is generated from burning uranium fuel in the reactors. HLW contains fission products and transuranic elements that are generated in the reactor core. HLW accounts for 3% of the total nuclear waste that is generated but accounts for 95% of the total radioactivity. HLW can be categorized into two different types:

- Depleted Fuel
- Waste from reprocessed used fuel

HLW contains short and long-lived components and is generally considered a hazard for people. When referring to LLW in Table 1 it encompasses VLLW and LLW together as LLW. The Figure 1 shows that LLW accounts for over 92% of the total nuclear waste produced, and as mentioned the different applications of nuclear energy all produce LLW waste making it critical that is it disposed correctly.

2.3 Types of Radiation Emissions:

The different types of waste classification mentioned encompass four different types of radiation that occurs. Alpha (α), beta (β), gamma (γ), and neutron radiation. Depending on the type of radiation being dealt with, it represents unique challenges for handling and containment.

Alpha and beta radiation, for instance, have lower penetration abilities compared to gamma radiation, which can easily penetrate materials, as shown in Figure *3* . Different radiation emissions have different methodologies and techniques for handling, and these must be replicated in automation to ensure they are accurately and safely measured.

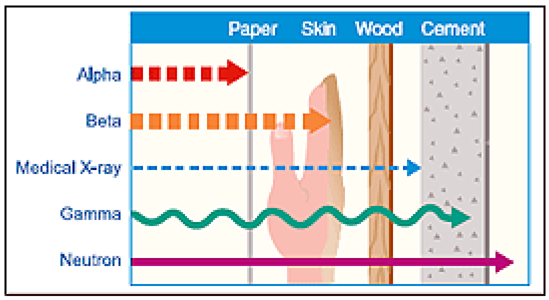

Figure 3 Penetration strength of nuclear radiation emissions

Alpha radiation occurs when an alpha particle is emitted from an atom during decay. An alpha particle is essentially a helium nucleus consisting of two protons and two neutrons is positively charged. Due to its low penetration strength from Figure *3*, alpha particles can be stopped with as little as a sheet of paper or stopped by a few centimeters in the air (*Alpha Particle Mass - Definition, Values, Example, Practice Question and FAQs*, n.d.).

Beta radiation is the emission either of a negative or a positive charged particle from the atom. In an unstable atom nucleus, a neutron can be converted to either an electron β^- or positron β^+, two forms of beta decay. Materials made from High Z (elements with high proton counts) elements cannot be used to stop beta radiation as it may result in bremsstrahlung interaction, producing X-rays. Therefore, low Z materials is used to stop beta emissions (*Beta Decay - Definition, Examples, Types, Fermi's Theory of Beta Decay*, n.d.).

Gamma radiation is the emission of high energy photos originating from the nucleus of the atom as it transitions to a lower energy state. Gamma and X-ray radiation are similar, gamma radiation results from the nucleus, while X-ray is a result of an electron interaction with the nucleus. Gamma radiation requires materials that have high Z number to effectively prevent penetration similarly to x-rays such as lead (Helmenstine, 2024).

Neutron's radiation is caused by the emission of neutron particles from the nucleus of the atom. Neutron radiation has no charge, similarly to gamma radiation. Neutron radiation has the highest penetration of all the types of radiation and is the only radiation that can make the object that of impact radioactive (*Radiation -- ANS / About Nuclear*, n.d.).

2.3.1 Radiation Safety

Now that we have discussed the different types of radiations, we move on to radiation safety. There are two main types of exposures, internal and external exposures. Internal exposure occurs when radioactive dust or gases enter the body and irradiate it from within the body. Radioactive particles can be inhaled, ingested or absorbed through skin contact. External exposure occurs when a person is physically close to the source of radiation. The radiation travel through the air and irradiates the person (Canada, 2019). Alpha radiation for instance can classified as loose contamination allowing it to be inhaled (*What Are The Different Types of Radiation?*, n.d.). It is critical to be aware how the radiation affects a worker to prevent prolonged exposure. The effective dose limits for a nuclear energy worker in Canada is limited to $50\ \mathrm{mSv}$ or $0.05\ \mathrm{gray}$ in a year or $100\ \mathrm{mSV}$ or $0.1\ \mathrm{gray}$ in five consecutive years. For pregnant workers the dose limit is reduced to $4\ \mathrm{mSv}$ form when the pregnancy is declared to the end of term (Commission, n.d.).

2.4 How does Laurentis Energy Partners Sort Low Level Nuclear Waste?

We have discussed a brief understanding of LEPs sorting process in the introduction. For implementing automation, it is important that we fully understand the process LEP has in place for LLW sorting. Figure 5 shows the floorplan of LEP and Figure 4 represents the process used. It is to be noted the process is based on observations I made at LEP.

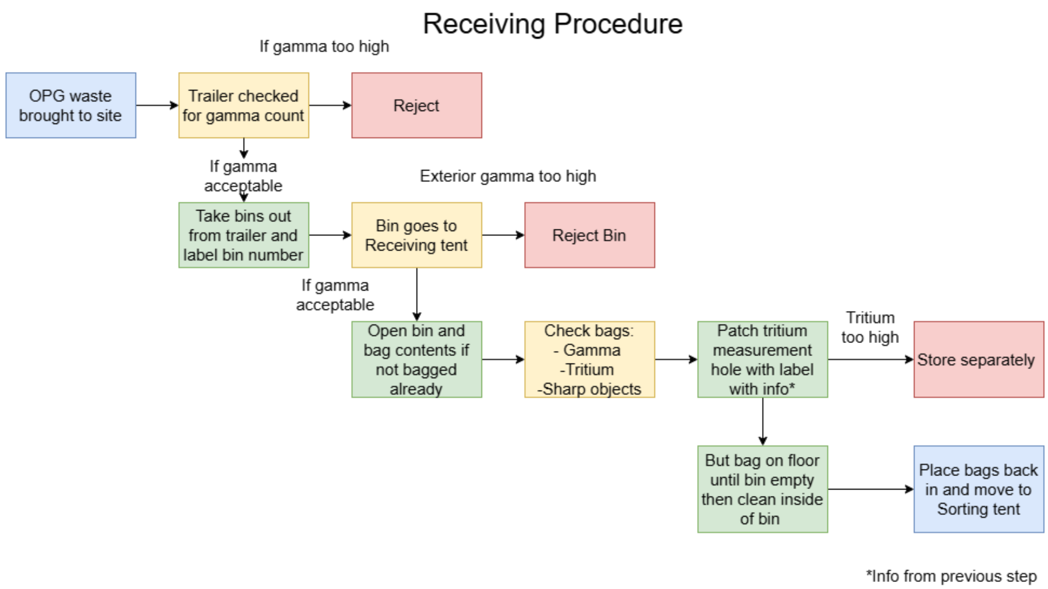

Figure 4 General Breakdown of LEP Process

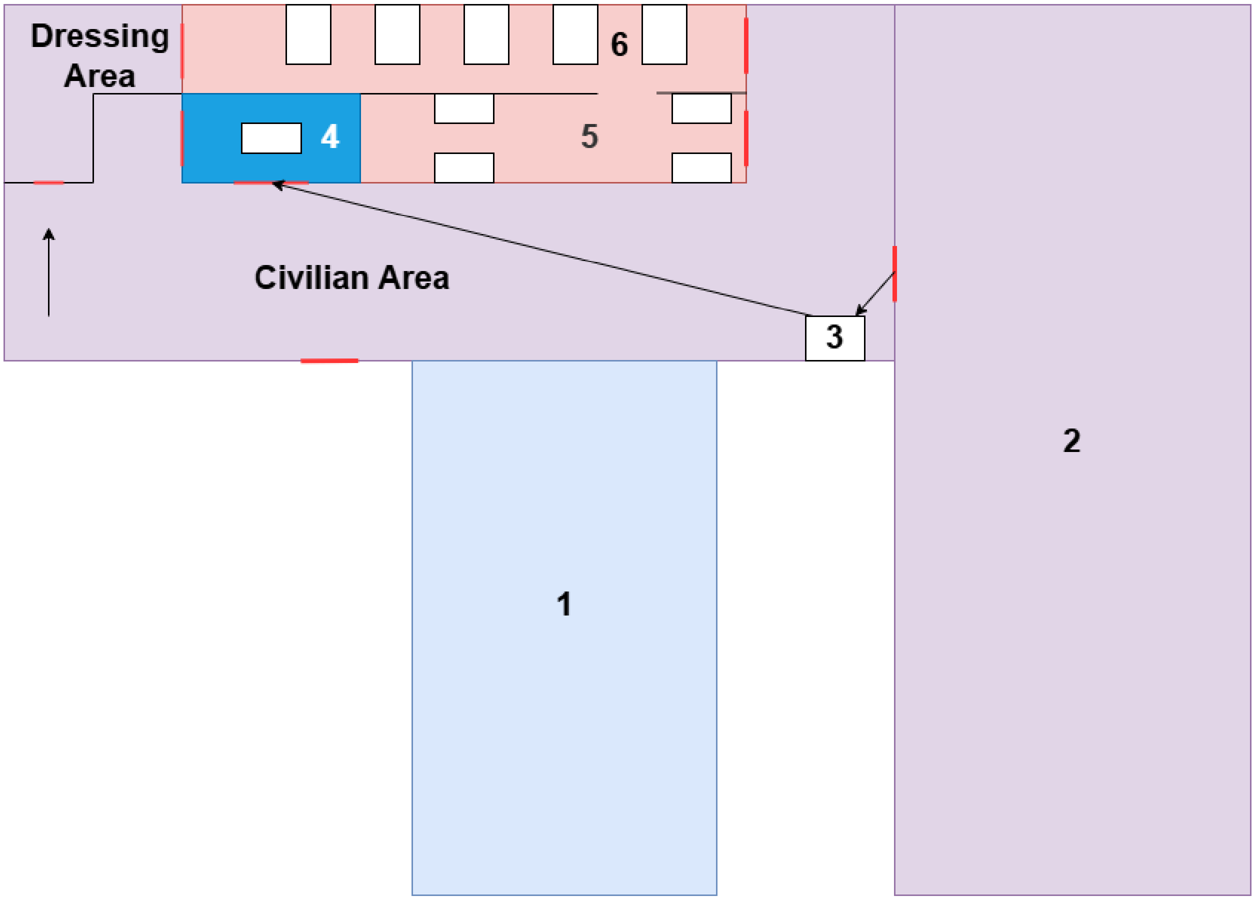

Figure 5 Floor Plan of LEP

The facility premise is broken down into two main sections: the purple, the blue and the red. The purple area is where radioactive material is processed, and the blue area is a radiation free zone. The red section identifies where radioactive material is sorted and is protected by a negative pressure vacuum dome to ensure radiation content is contained within the dome. The purple section's "Dressing Area" is where technicians prepare to enter the sorting tent. The red lines represent entrance/ exit to the area. Within the colored sections there are numbers mentioned in the diagram that corresponds to the following:

1. Radiation free zone where the offices in the building are. No waste to be entered into this region.

2. Identifies a large storage facility where the initial Low-Level Waste (LLW) arrives in large metal containers from Ontario Power Generation rectors into LEP. Waste sorted in red region is placed here after.

3. First stops for initial radiation test after container is brought in from storage facility. The container is checked for gamma radiation on all sides of the bin. The container must pass this step prior to moving forward to bin measurement room (BMR).

4. Second stop after initial radiation tests are completed and is cleared for sorting. This is referred to as the bin measurement room (BMR). Figure 10 provides a detailed diagram.

5. Third stop after the bin is cleared in the receiving section, it moves down to the sorting tents. Technicians will begin to open the bags and categorize the waste.

6. Fourth stop after waste is sorting, there are bins with the corresponding disposal categories. Workers will place sorted waste bags into these respective bins. Once these bins are filled, a forklift will carry the waste and place them into the large storage facility awaiting to be taken away from the facility.

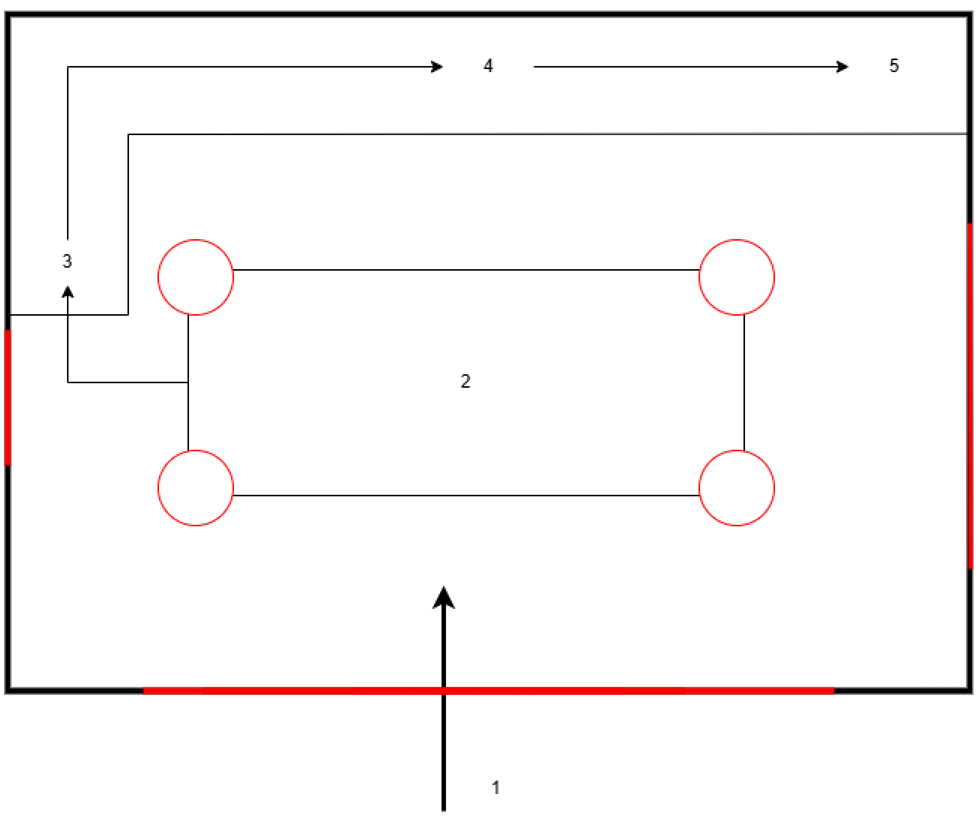

Figure 6 Layout of Bin Measurement Room

Figure 6 provides a detailed view of Area 4 also known as the bin measurement room (BMR) from *Figure 5*. This is where bins arrive at the sorting tent with unknown amount of radiation levels and are tested to ensure waste can be processed.

1. Initial entrance for unsorted bin.
2. The bin is initially checked for Tritium concentration, by lifting the lid from each corner allowing insertion of a Tyne 7043 probe. Locations where tritium concentrations are measured are indicated as red circles. Gamma radiation measurements are taken from all side of the bin except the bottom one. When tritium, gamma radiation, alpha radiation measurements (Gamma detector measures both) are within the facilities specification to handle, the lid is removed to begin sorting. The bags are removed one at a time and the exterior of the bag is cleaned to remove surface level contaminates. This prevents it from spreading everywhere in the room. Once all bags are removed from the bin, the bin is cleaned from the inside, removing any surface contaminates that may be present.
3. At this station cleaned bags are taken, and a table is applied which contains the bin number and the bag number as a unique identifier.
4. At this station each bag is then scanned by a technician for a gamma measurement using the BOT Engineering P200 detector, and the measurement is manually recorded by the technician.
5. Final station takes a tritium measurement. A small hole is pierced into the plastic bag to insert the probe of a BOT Engineering RM-P1000 to make a measurement, a 30 second measurement is taken, and a value is recorded manually by the technician. A label is attached to the bag covering the hole with the measurements from gamma and tritium. The bag is then placed back into the cleaned bin. The cycle is repeated for the remainder of the bags.

This concludes who LEP is, and the work they do. The significance to this thesis is how the process is executed. LEPs entire process is manually executed by workers. All activities mentioned in Figure *5* and Figure 6are accomplished by workers. The workers use a piece of paper that logs all the bags and their respective gamma and tritium radiation levels, and at the end of the bin the values are manually entered into a spreadsheet in Excel by another worker. Workers use radio communication to notify the sorting section, and the main office that a bin is completed.

Throughout their process in the bin measurement room (BMR) there are multiple points where errors can be made, specifically human related errors in reading and interpretation of values. Additionally, every person has a different thought process further adding to the error (De Felice & Petrillo, 2018). The BMR is the focus for the thesis as automation can bring improvements in this room with respect to automated measurements.

2.5 Significance of Automation

Automation has become the backbone of many industries. Across the different industries, automation has brought improvements that aid accuracy, efficiency, and productivity, and nuclear waste management is no exception. In LLW sorting, Industry 4.0 technologies such as the Internet of Things (IoT), wired and wireless communication protocols, and real-time data collection systems can provide benefits in improving measurement accuracy and operational safety. Implementing Industry 4.0 technologies, automation systems can be utilized to perform radiation measurements, parallelize multiple tasks, and improve process repeatability allowing to reduce worker exposure to prolonged radiation exposure at LEP facilities. Industry 4.0 refers to the fourth revolution which arrived for the industrial revolution. The first industrial revolution started in Britain during the 18th century, primarily enabling humans to enter the era of production using steam power for the first time opposed to the water mills that had been used prior to then. Industry 2.0 is the first time we introduced assembly lines, and the first-time communications had started to get widely adopted primarily using telephones and telegraphs. The third industrial revolution brought high telecommunications and data analysis into manufacturing. The Programmable Logic Controller (PLC) was introduced during this time allowing automation of machinery. Small low powered microcontrollers are also being used to power IoT based devices, just as Raspberry Pi, Arduino, and many other Arm and x86 based devices for high compute requirement can also be used.

2.5.1 Benefits of Automation for LEP:

Automation can benefit LEP in the BMR. To reiterate in the BMR LEP checks gamma and tritium for incoming bins, initially on the exterior surfaces of the bin, and tritium measurements within the bin using a small gap between the lid and the bin. If the gamma and tritium measurements are within range of LEPs operating range, the lid is removed, and the contents are re-bagged. The process of which can benefit from automation, is how the re-bagged bags are weighed, and checked for gamma and tritium measurement. Additionally, automation can aid in ensuring consistent measurements are being performed.

To begin implementing automation in the BMR it is important to understand the tools that are used by LEP. For measurements handheld detectors are used, and a survey of the bag is done to determine a value, which is interpreted by the workers and not the tools. LEP uses several types of detectors, and each detector can use a different methodology on how it measures gamma radiation.

2.6 Types of Detectors

Given the complexity and manual nature of LEPs measurement process, it is crucial to understand the available methodologies that can be used for gamma radiation detection. There are three types of common techniques that are used to detect gamma radiation. Each of the techniques have different methods of detecting a charged particle, in this case a gamma radiation. Each of them have a different working principle and excel in different applications. It is important to the LLW waste apparatus that an appropriate detector is selected, and this includes how it measures gamma radiation. In The next sections the following detectors will be discussed: Scintillation Detector, Geiger-Muller Counters (GM), and Semiconductor Detectors (Solid State Detectors).

2.6.1 Scintillation Detectors:

The working principle of a scintillation detector consists of ionizing radiation interacting with the scintillator material. This excites the electrons to a higher energy state. In the case of charged particles, the particles themselves creates a track and for uncharged particles such as gamma rays, their energy gets transferred to an electron using either one the three processes photoelectric effect, Compton scattering or pair production. The light produced from the interaction is captured in a photomultiplier tube (PMT) producing a pulse. The number of pulses is captured as a measurement. One great thing about a scintillation detector is their high efficiency fin measuring gamma rays. Some of the downsides of scintillation detector include: susceptible to temperature changes and requires stabilization. Scintillation detectors can also be used for alpha and beta radiation measurements. They are primarily used in medical imaging, radiometric assay, nuclear security and nuclear plant safety. Figure 7 (*Scintillation Counter -*

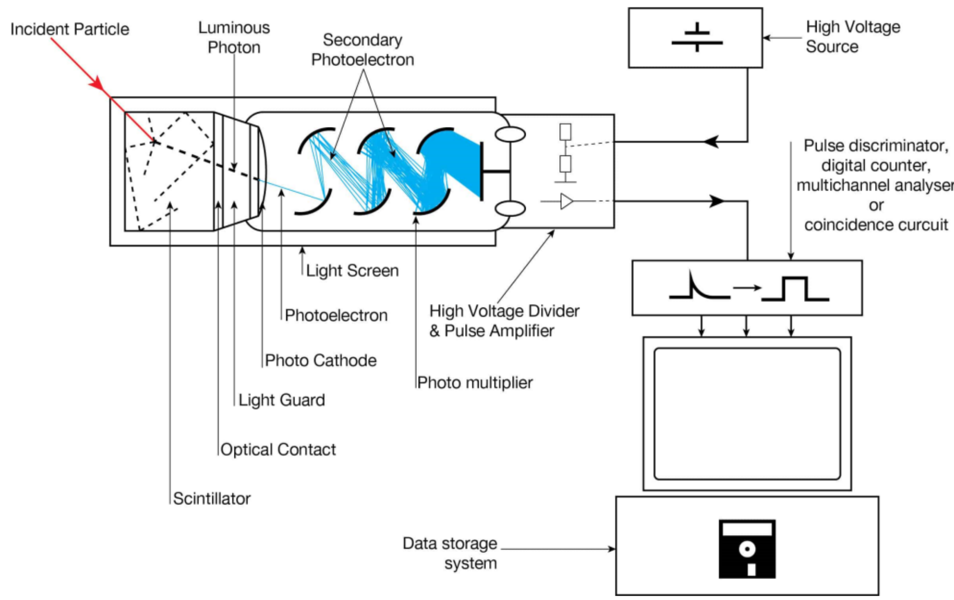

Figure 7 Basic Breakdown of a Scintillation Detector

Scintillation Detector | Nuclear-Power.Com, n.d.) illustrates a breakdown of a scintillation detector, and the key components that are associated with it.

2.6.2 Geiger-Muller Counter:

Geiger-Muller (GM) detectors can detect alpha, beta, gamma radiation, and neutron radiation. The working principle for such a detector includes a pair of electrodes placed in a chamber surrounded by a gas, typically argon or helium. Radiation particles enter the chamber and ionize the gas, producing an electric current. The electric current is measured as a count. GM counters are sensitive, allowing to measure low energy gamma rays and beta particles.

(Stroski, 2023) shows the basic explanation of how a gamma ray interacts with a GM counter to produce a count. A GM detector has three states it can operate in: proportional, plateau and continuous discharge regions. For a GM detector to be used a detector it must operate in the plateau region (*Geiger Muller Counter*, n.d.) Figure 8 (*Geiger Muller Counter*, n.d.)

illustrates a visual representation of the operating states with respect to applied voltage compared to count rate.

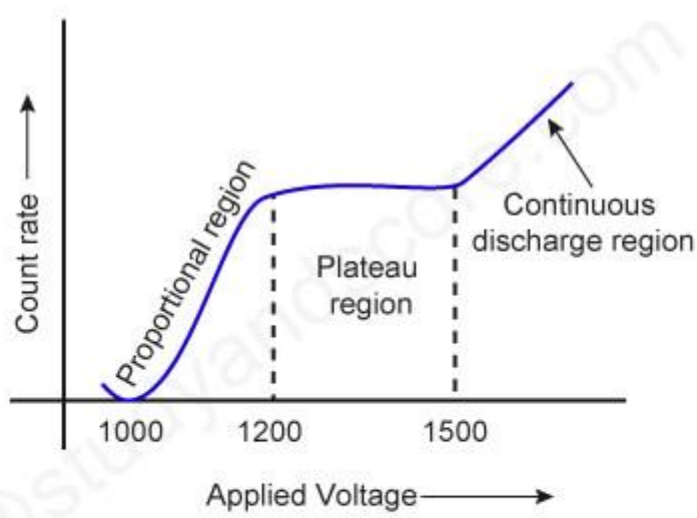

Figure 8 Geiger-Muller Counter Stages of Operation

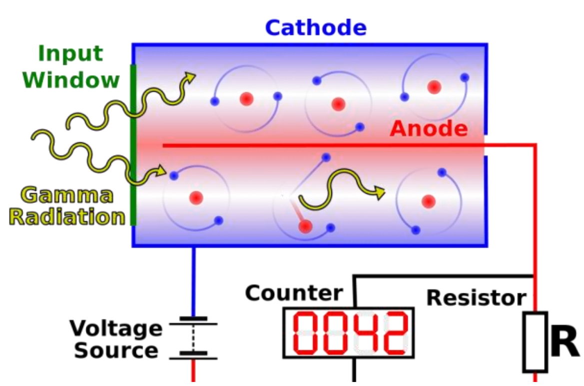

Figure 9 Basic diagram of Geiger Muller Counter

2.6.3 Semiconductor Detectors (Solid State Detectors)

Semiconductor detectors are also known as High Purity germanium detectors (HPGe detectors). They are best known for its applications in gamma and x-ray spectroscopy. As the name suggests, semiconductor detectors use a semiconductor material for detecting gamma radiation. The semiconductor portion has a band gap between 1 to 5eV. The basic working principle is interaction between the germanium crystal and radiation particle. The interaction causes semiconductor atoms to get ionized producing electron hole pairs. The electron hole pairs are proportional to energy of the incident ionization radiation. In the presence of an electric field the electron holes travels to the electrodes where it creates a pulse that can be measured by an external circuit. The pulse contains information about the incident radiation resulting in a gamma radiation reading. Figure 10 (*Ionizing Radiation Detection and Spectrometry*, n.d.). shows the basic diagram and building blocks of a semiconductor detector including the semiconductor portion.

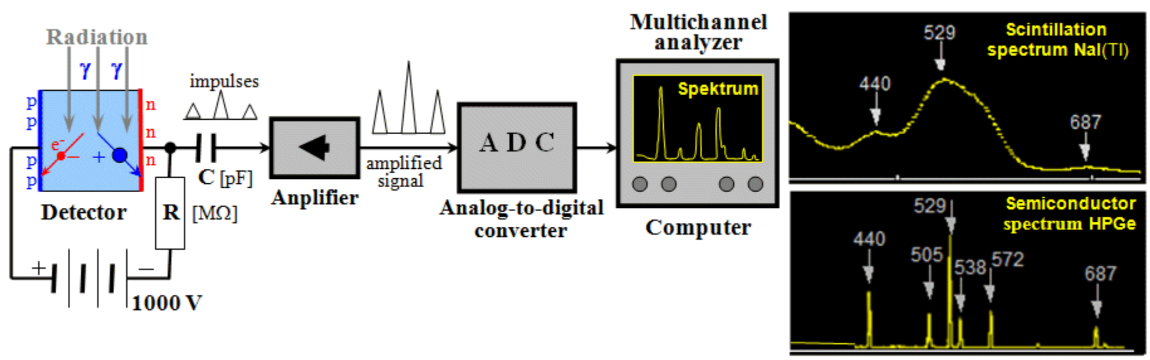

Figure 10 Basic Diagram of a Semiconductor Detector

2.6.4 Summary of Pros and Cons

Table 2 illustrates the advantages and disadvantages of the three types of detectors that have been mentioned. Semiconductor detectors provides the best resolution but is the most expensive. Geiger-Muller detectors are the cheapest from the three but cannot provide energy information, and when exposed to high radiation fails to provide details. Lastly Scintillation detectors provide a middle ground between the three but are susceptible to moisture.

Table 2 Pros and Cons of Different Gamma Detectors

Detector Types	Pros	Cons
Scintillation Detectors	• High sensitivity allows for lower energy detection, versatile, and quick response.	• Requires a PMT, low resolution, is susceptible to moisture.
Geiger-Muller Counters (GM)	• Simple, allows for lower radiation energy detection, cheap and small footprint.	• Provides no energy information, cannot provide details at high level of radiation, limited endurance
Semiconductor Detectors	• Great for spectroscopy, provides excellent resolution	• Expensive, requires active cooling, and is sensitive to environmental conditions

(*Detection of Gamma Radiation - Detector of Gamma Rays | Nuclear-Power.Com*, n.d.)

2.7 Detectors Utilized at Laurentis Energy Partners

The objective of the thesis to implement automation into the BMR. It is crucial to understand the equipment that LEPs employs in their facility. This provides insight to the accuracy and rate of detection that LEP expects from their detectors. Additionally, it provides a starting point for companies that manufacture detectors. Determining the detectors that is used by LEP allows us to understand if they can be implemented into an automation system. The next sections discuss detectors that are used at LEP, they are broken down into two categories gamma measurement detectors, and tritium measurements detectors. Additionally, detectors outside of LEP are explored to get a better understanding of what's available.

2.7.1 Gamma Measurement Detectors:

Table 3 Gamma Detectors Present at LEP

 RDS-31iTx	This is a Geiger-Muller gamma detector, alpha and beta emissions can be measured with an external probe. This detector is NOT used in the BMR as it is considered too slow by LEP. This device can be used for remote monitoring and automation using an external device which can connect to multiple RDS-31iTx simultaneously and monitor the values measured by the individual detectors and allow a computer to see them. This device uses ZigBee communication to send data to the main base (*2096_6891_rds_31itx_user-Manual_eng_v1_11.Pdf*, n.d.). LEP does not use this detector in this configuration. The unit of measurement for this detector is $\frac{\mathbf{\mu Sv}}{\mathbf{hr}}$.
 P200 Body and Detectors	This is a Geiger-Muller gamma detector and can only measure gamma radiation. This detector is the main detector in the receiving tent due to its fast response at low gamma counts. Detector supports no means of communication to an external device such as a computer. There are no ports or adapters that can be used either. There is two parts to this device, the probe can be changed but the base cannot be changed (*BOT ENGINEERING – Bot Engineering*, n.d.). Depending on the application the detectors can be changed. It measures in $\frac{\mathrm{mREM}}{\mathrm{hr}}$.
 Bot Engineering RM-P1000	This is a portable detector like the RDS-31iTx. This device like the Bot engineering P200 has no support for data communication to a computer. This device is not used in the receiving tent. It measures in $\frac{\mathrm{mREM}}{\mathrm{hr}}$.
 Figure 11 Canberra 1000 Gamma Spectrometer	This is a scintillator detector NaI based. This detector is not used at LEPs. This is a device owned by the McMaster Health physics. This primary use it is gamma spectroscopy but has the ability to measure gamma as a scintillator detector. This is a rather large device, as it contains a small computer on board which process the information from the detector and show it as a spectroscopy.

Analysing the detectors that are being used by LEPs indicates that most are incapable of being implemented into automation systems as is. Tyne 7043 is the only detector that supports reading values from the detector to a computer. As a result, detectors outside of what LEP utilizes in their facility were researched. Primary focus was to have serial or digital connectivity such that it can be incorporated into an existing microcontroller or PLC setup for automation. The detectors explored have been identified such that they can be integrated into automation with ease.

2.7.2 Tritium Measurement Detectors:

 Figure 12 Tyne 7043 Gamma and Tritium Detector	This is a tritium detector with quad ion chambers, it also measures gamma radiation using Geiger Muller counter method. The device supports data logic capability over serial communications RS232/RS485 and supports 0-5V analog output for the reading. This is one of the two tritium devices at LEP. This one is not used in the receiving tent as it is considered slow due to the air having to travel through 4 ion chambers but is the more versatile and accurate option. It is slower than the Overhoff Model, as it has twice as many chambers for the air to flow through. Figure *12* shows the detector, and the respective serial communication ports on the rear of the unit (*Portable Tritium-in-Air-Monitor*, n.d.).
 Figure 13 Top view of Overhoff Model 200	This is a tritium detector with dual ion chambers. One chamber is used to provide compensation for gamma radiation. Provides final reading within 5 seconds from a step response from an aspirated tritium. The device does not support supports serial communications to send values to a computer. This is one of the two tritium devices at LEP, this one is used in the receiving tent as it is considered fast due to the air having to travel through only 2 ion chambers. This is the faster and less accurate of the two. *Figure 13* shows the Overhoff Model 200 with the pump and display, it has a sensitivity of medium sensitivity: $10\ \mu\frac{\mathrm{Ci}}{\mathrm{m}^3}$, 1 MPCa, or $0.4\frac{\mathrm{MBq}}{\mathrm{m}^3}$ and has a wide range of 10 to $199{,}990\ \mu\frac{\mathrm{Ci}}{\mathrm{m}^3}$, 0.1 to $1{,}999.9\frac{\mathrm{MBq}}{\mathrm{m}^3}$, or 1 to $19{,}999$ DAC/MPCa (*Model 200SB | Tritium Monitor*, n.d.).

2.7.3 Additional Detectors Researched:

2.7.3.1 Mirion NAIS-3x3:

Figure 15 is Mirion NAIS, a scintillation-based detector integrating the high-voltage power supply (HVPS), preamplifier and digital multichannel analyser (MCA) into a single package. It is compatible with the standard 14-pin connector (Figure 14) scintillation use including 10 stage PMT such as NaI(Ti) and LABr3(Ce) detectors. It supports USB 2.0 and power over ethernet for plug and play applications and supports networked applications. This detector also supports data readout and collection (*NAIS-3x3*^{TM} *NaI LED Temperature-Stabilized Scintillation Detector*, n.d.).

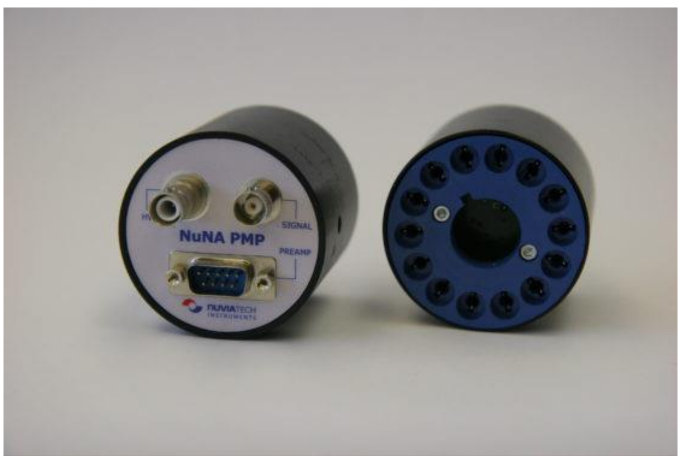

Figure 14 Standard 14 Pin Scintillator Connector

Figure 15 Mirion NAIS-3x3

2.7.3.2 Bot Engineering AR-600:

Figure 16 is a gamma monitoring alarm system first and a device to read values from detectors second. This is a device that is meant to be placed to measure gamma radiation and ring an alarm if radiation levels go above the set threshold. AR600 can also be used to read gamma radiation values from the inbuilt detector or an external detector (Note both cannot be used at the same time). The external device connects via an ethernet cable (unknown protocol used). It supports the same detector probes as the P200 but required an adapter in between. The device essentially houses the brain of the P200, so the speed and accuracy are the same as the P200 which is actively used in the receiving tent. The serial readout rate is 1 Hz. Bot engineering was quick to loan us this device for testing.

Figure 16 Bot Engineering AR600

2.7.3.3 VF Nuclear SGN-02:

Figure 17 is a plastic scintillator detector which has a gamma measurement range from $100\,\frac{\mathrm{nSv}}{\mathrm{hr}} \rightarrow 40\,\frac{\mathrm{mSv}}{\mathrm{hr}}$ it has an energy range of $100\ \mathrm{keV} \rightarrow 10\ \mathrm{MeV}$. It requires a 24V input power and is capable of communication using a RS-485 cable (serial communication), and it weighs 2.7 kg. The operating temperature is between $5°\mathrm{C} \rightarrow 45°\mathrm{C}$, the detector can also be used for spectrum analysis which may come in as a bonus.

Figure 17 VF Nuclear SGN-02

2.7.3.4 Kromek EV-CPG:

Figure 18 Kromek EV-CPG is a CZT-based gamma detector that is meant for gamma spectroscopy but can also be used for gamma dose rates. These detectors provide high energy resolution from $30\mathrm{keV} \rightarrow 2.0\mathrm{MeV}$. The detector requires 12VDC input and a 1200V bias connection.

Figure 18 Kromek EV-CPG

2.7.3.5 Kromek D3 Personal Radiation Detector:

Kromek Personal Detector Figure 19 is a crystal detector instead of a GM. This detector can be used for a single point or multiple integrated sensors together either using USB or Bluetooth no external device required. It is battery operated allows for 40hr using AA batteries.

Figure 19 Kromek Personal Detector

2.7.3.6 Kromek GR1 Radiation Detector:

This is a CZT (Cadmium Zinc Telluride) based detector that can be powered from a USB cable alone and the data can be read using a computer. However, to automate this device an expensive software driver is required to be purchased from Kromek which allows to get useful readings from the detector. This detector costs between £8000-£12000 plus £2125 for the driver. The small compact price comes at a significant cost. This was one of the most expensive detectors.

Figure 20 Kromek GR1 Radiation Detector

Reviewing the detectors indicates that each of the manufacturers provides different information in their respective data sheets. While some provide measurements ranges in sieverts, others provide ranges in electron volts, and for others there is no ranges provided. Sieverts is a measurement of biological impact whereas electron volts are a measurement of energy. The two units are not directly comparable. The key information about the detectors abilities to communicate with a computer were provided in the datasheets, but the communication protocols were not mentioned making it difficult to gauge if it can be implemented.

2.8 Communication Protocols

Now that we have explored detectors that are actively being used at LEP, and potential automation ready detectors. Some of the detectors deployed at LEP such as the Tyne 7043 support wired serial communication. Additionally, from other detectors explored, the Bot Engineering AR-600, Mirion NAIS-3x3, VF Nuclear SGN-02 and Kromek D3 all support wired communication. It is important to understand communication methods for transferring data between detectors and a host computer. There are two methods for communication either wired or wireless. In order for the automation to work the detectors must be able to communicate with a host computer either wired or wirelessly. Within wired and wireless communications there are multiple different protocols that can be used for data communications. Wired communications the following different protocols are explored:

2.8.1 Wired- UART

Universal Asynchronous Receiver-Transmitter (UART) is a common and widely used communication protocol (*UART: A Hardware Communication Protocol Understanding Universal Asynchronous Receiver/Transmitter | Analog Devices*, n.d.). It is highly used in the embedded system area. The key features of UART us that it provides a means of asynchronous data transmission while utilizing two wires, packet-based data transmission, and ensuring that a common baud rate is being used between the master and slave setup where the master is the part requesting information from the salve address. The baud rate is configurable based on the application, and the master and slave baud rate (the speed at which data is transmitted between devices) must be the same for communication to occur, it is the rate at which information is transferred. UART supports UART must be present and enabled on the microcontroller to be able to use the UART protocol.

2.8.2 Wired- SPI, I2C

Serial Peripheral Interface (SPI) and Inter-Integrated Circuit (I2C) are two protocols that allows for a microcontroller to communicate with different peripheral devices. These devices can be sensors or other controllers and memory chips such as read only memory (ROM). From the two SPI is faster and is capable of full-duplex communications at the expense of more pins. I2C is much slower but like UART only requires two pins and or lines SCL and SDA. I2C can allow multiple slaves on the same network with one master, allowing one device to control multiple devices. Table *4* provides a breakdown between 3-wire and 2-wire and their respective advantages and disadvantages while Figure 21 illustrates I2C with multiple devices connected on the same bus (*SPI/I²C Bus Lines Control Multiple Peripherals | Analog Devices*, n.d.).

Table 4 Summary of Pros and Cons of Wired Communications

Interface	Advantages	Disadvantages
3-Wire: SPI, QSPI, and MICROWIRE PLUS	• Speed • Pull up resistors not required • Full-Duplex operation • Noise Immunity	• Requires larger number of bus line connections • Individual chip-select lines required to communicate with more than one slave at a time • No confirmation of received data.
2-Wire: I²C and SMBus	• Requires fewer bus line communications. • Can have multiple devices on the same bus. • Confirmation of received data.	• Speed: SMBUS 100khz, I2C 3.4MHz • Lacks full-duplex communication. • Requires pull up resistor. • No noise immunity.

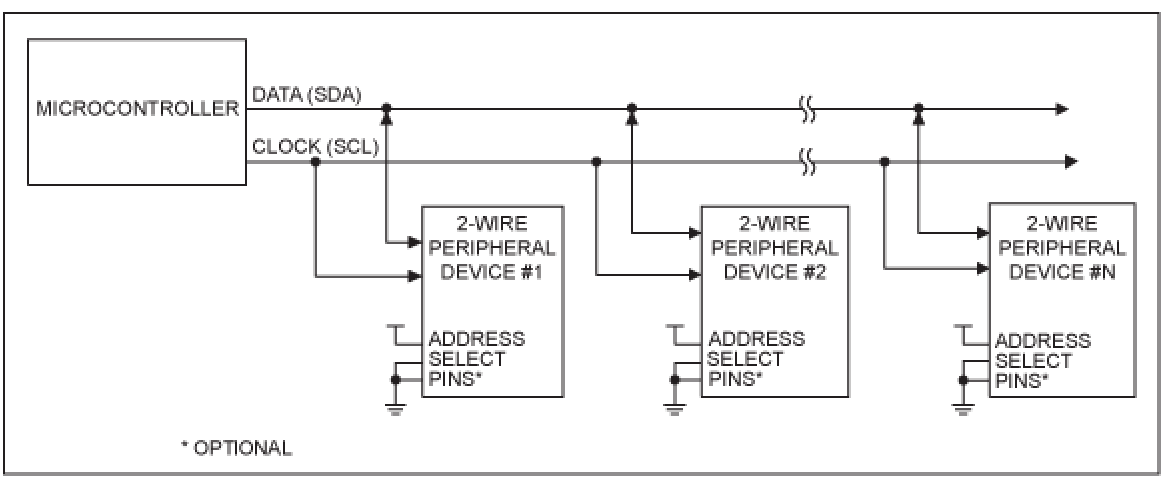

Figure 21 I2C Sample Diagram showing multiple devices on the same bus.

2.8.3 Wired- RS 232

RS 232 is a serial communications method that is primarily used in legacy computer peripherals such as printers, scanners, and modem, but is also used in the industrial automations for PLC and HMIs. The are also found on testing and measurement equipment such as multimeters and oscillators. RS232 supports up to 192000 bits per second (115200 bps typically) with a minimum of 1200 bps (Singh, 2024). This communication has a limit on the maximum length the cable can be at 15 meters. It is more ideal for short distance. RS 232 supports 15V making it ideal for PLC applications but not necessarily for microcontrollers.

Figure 22: RS 232 Cable

2.8.4 Wired- RS 485

RS 485 is a much faster serial communication method at 10 Mbps. It is a differential serial communication intended for long range communication. RS 485 is much more flexible in terms of its range of data communication ranging from 300 bps to 10 Mbps making it versatile. This communication has a maximum distance limit of 1200 meters making it much better for long distance communications. RS 485 supports having multiple masters and slave on the same bus, allowing for multiple microcontrollers / PLCs being able to control multiple other devices while being attached to the same bus (Sonee, 2020). It shares the same connector as RS 232 but has a different pin out, as it uses differential signaling. The primary uses for RS 485 is in industrial automation, building control systems, and networking applications. RS 485 supports 15V making it ideal for PLC applications but not necessarily for microcontrollers.

2.8.5 Wired- RS 422

RS 422 is like RS 485 with one key difference being in the operation voltage which is reduced to 5V making it more microcontroller friendly.

One of the key objectives for the thesis is to reduce workers' radiation exposure. Incorporating wireless communications/IoT protocols is one method that can help obtain the objective. To select the appropriate communication protocol, it is necessary to understand them, as the automation needs to be adapted to it. The microcontroller is heavily affected by the wireless communication, as not all controllers support all protocols. Specifically, for the LLW Sorting Apparatus, we dive into; Wi-Fi, Bluetooth, Zigbee, Long Range (LoRa), and MQTT, as these are some of the protocols that are used in the nuclear energy industry.

2.8.6 Wireless- WI-FI

Wi-Fi is a broad umbrella that contains many different versions and specific uses. For this paper, we will discuss Wi-Fi as applied in IoT applications. Wi-Fi is based on the IEEE 802.11n (there are other faster standards, 802.11ac), which is commonly used in homes; phones, computers, TVs, and other devices all utilise this to connect to the internet. Wi-Fi operates in the 2.4 GHz and 5 GHz bands with other newer bands that are outside the scope of this. Wi-Fi has a tremendous range of 50m to 100m with high data rates and a speed of 600 Mbps on the upper end. 802.11ac will offer higher speeds (Sonee, 2020).

2.8.7 Wireless- Bluetooth

Like Wi-Fi, Bluetooth also operates on the 2.4 GHz band. It has a range of 50 m to 150 m: the lower the bandwidth, the longer the distance. Bluetooth low energy (BLE) has a range of 150 m (Sonee, 2020). Bluetooth is known for being used in short range applications for sending small data chunks for personal devices but can be used for other industrial applications. The Bluetooth Low Energy for Industrial Automation paper talks about the implementation of BLE in industrial and process automation, where BLE is shown to be used to retrieve data wirelessly from a substation room, simplifying the data acquisition and storage(Grover et al., 2015). This makes it viable to use in the automation of a waste sorting facility.

2.8.8 Wireless- Zigbee

Zigbee is a wireless communication protocol designed around low power applications. It is based on the IEEE 802.15.4 standard. The primary uses for this protocol are in home automation, smart lighting, security systems, and lastly, industrial automation control systems. The key features of this protocol are low power consumption, low data bandwidth, and mesh networking, allowing more multiple ZigBee enabled devices to talk to each other, provided vast scalability, and the last devices that use ZigBee can be manufactured agnostic. Zigbee can be used in remote background radiation monitoring applications (Adamu & Muazu, n.d.), allowing it to be calibrated for background radiation. This makes it viable to be used in nuclear applications.

2.8.9 Wireless- Long Range (LoRa)

Long Range (LoRa) is a technique in spread spectrum modulation that was derived from chirp spread spectrum (CSS) owned by the company Samtech (*LoRa PHY | Semtech*, n.d.). The

LoRa silicon is designed by Semtech and follows the LoRaWAN standard, which is operated by LoRA Alliance. LoRaWAN helps enable IoT in energy management, natural resource reduction, pollution control, infrastructure efficiency, and disaster. This is because the devices that utilize LoRa require minimal power and can stay active for prolonged periods of time allowing to gather data for extended periods of time which in return improves the intended applications. For example LoRa in electricity measurement devices in residential communities allows for the electricity companies to actively monitor the consumption at any given time allowing them to optimally buy electricity from the providers, and charge the customers accordingly. LoRa devices are used to enable smart cities in homes and buildings and are used to send power meter values to the city. It is also used in the agricultural sector. LoRa has previously been used for environmental radiation monitoring, as mentioned in (Manzano et al., 2021). In this specific scenario, LoRa was used to measure the radiation levels in waste containers on a continuous basis and send information back periodically to a LoRAWAN network server. The network was created over hundreds of hectares of land, proving it is suitable for long distance remote monitoring.

2.8.10 Wireless- MQTT:

MQTT stands for Message Queuing Telemetry Transport. MQTT is a messaging protocol used in scenarios where clients require a relatively small code and are constricted by low bandwidth. It is typically used for machine-to-machine communication or IOT applications (*What Is MQTT?*, n.d.). It runs on the Transmission Control Protocol (TCP) and/or Internet Protocol (IP). Both use the client-server method of communication. In MQTT, there is the subscriber and publisher. MQTT is managed by the Organization for the Advancement of Structured Information Standards (OSAIS) standard messaging protocol for the Internet of Things. A client is any device is any controller or server that can connect to the MQTT Broker. The client is the device that is gathering information using sensors or other means and is then publishing that data to the broker. A client can also be a subscriber where it calls for information from the broker. The image below illustrates the concept.

The clients that act as the subscriber can be any device, PLC, computer, or cellphone. Any device that can use MQTT can act as a client in the from of a subscriber. The broker is the important aspect of MQTT. A well implemented broker can handle up to millions of MQTT clients. The broker is responsible for handling all the requests that come and is responsible for filtering the messages, determining what device is subscribed to each message, and sending the correct messages to the correct subscribed client. All clients must talk to the broker, they can not individually talk to each other. There are broker services that are free, and there are paid brokers as well. When security for data is required, a paid broker is required. Broker requires a username and password to either send or receive information. Each stream of data being sent to the broker is uniquely identified as a topic. A single device can publish different values using different topics. Figure *23* illustrates the different components associated with MQTT (*MQTT Publish/Subscribe Architecture (Pub/Sub) – MQTT Essentials*, 2023).

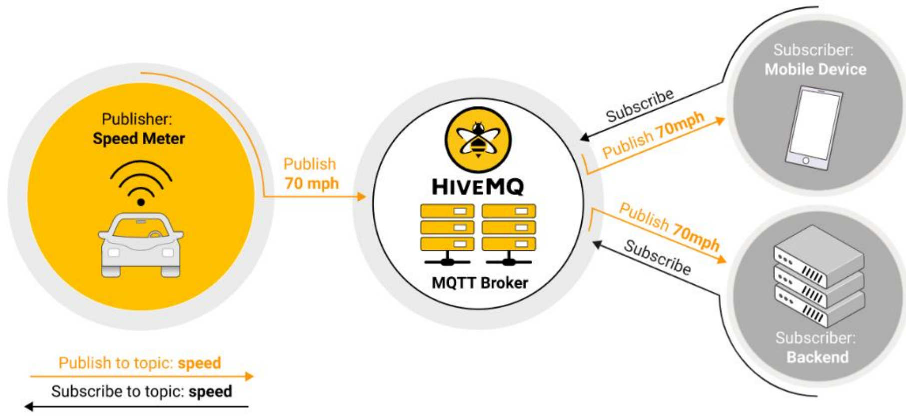

Figure 23 Breakdown of MQTT Components

There are applications for MQTT to be used in the automation, nuclear power plants, environmental gamma radiation monitoring system. Center for Nuclear Facilities Engineering at Serpong Nuclear Complex has developed a prototype which used an Arduino based gamma monitoring device, which transferred data using MQTT protocol. Data was stored in a PostgreSQL database and the data was visualised using a web-based user interface(Susila et al., 2018).

2.9 Automation Controllers

To create automation with repeatability ensuring the measurements can be repeated an automation controller is required which can be programmed to create a cycle for the apparatus. The cycle would dictate how the automation proceeds, what steps it take, and how long the automation runs for. An automation controller is required to accomplish this. There are two main types of controllers that are explored. Programmable Logic controllers (PLC) which are intended for automation purposes, and a Raspberry Pi, which is an arm-based microcontroller.

2.9.1 Controllers- PLC:

PLC stands for a programmable logic controller. PLCs are the common controller used in automation related applications. It relies heavily on standardized protocols that streamlines designers work thus making it easier. PLCs excel in tasks requiring large amounts input/output interactions. PLCs support a variety of automation communication protocols such as ethercat, IP/Modbus TCP, and traditional Modbus. PLCs suffer when complex data processing is required.

For example, a task such as taking 200 points of measurements and sorting that from min to max, and determining the average becomes quite challenging with PLC. Complex tasks require significant effort, while in Python it would only require a few lines of code. The additional of a computer with a PLC can simplify the process, this adds significant cost to the system. How ever there are PLCs sold that integrate PLC and a computer in a unit. Their cost can be as high as a gamma detector.

2.9.2 Controllers- Raspberry Pi:

A Raspberry Pi is a small low powered computer that runs Linux, Windows or other customized operating systems. It is cost effective and supports input/output using digital communications and comes with four USB ports on them that can be used to connect a detector such as the AR600. Raspberry Pi has onboard Wi-Fi and Bluetooth, simplifying communications with another computer relatively easy.

One limitation that the Raspberry Pi is its inability to measure analog voltage signals as it lacks an ADC (Analog to Digital Convertor)/ DAC (Digital to Analog Convertor). Figure 24 below shows an addon card installed on the Raspberry Pi enabling analog readings from 0-5V. The Raspberry Pi can satisfy the automation requirements for this project as it is able to read values from both the detectors and two analog devices simultaneously at a fast rate. In the paper Raspberry Pi, an Alternative Low-Cost PLC concludes that a Raspberry Pi can be used as a PLC alternative for low to medium sized automation projects (Andrei et al., 2020).

Figure 24 Raspberry Pi with ADC Hat Attachment

2.10 Human Machine Interface (HMI)

The best formfactor for the automation to reside is in an apparatus form. Where the bags can be loaded into prior to automation beginning. An interface is required that would allow for the worker to control the apparatus. In automation terms this is referred to as a Human Machine Interface (HMI). The HMI is point of contact between the worker and the automation. It allows the worker to fully control the automation and run specific tasks or cycles as needed.

Node-Red is a development tool that allows for visual programming. It was developed by IBM. The programming IDE can be accessed by any device with a web-browser. The development tool is created using Node.js, which allows for it to be programmed using JavaScript. It can be run locally on a specific device such as a Raspberry Pi, Arduino, or an android based device. Lastly it can also be running off a server, Microsoft Azure, Amazon Web services etc. Node-red needs to be installed on a device, and then is accessed using the web-browser. If it is correctly setup, you can access the IDE which is running on a server. Node-Red can be used to create an interface which can act like an HMI providing the controls needed to control the machine.

In conclusion, the automation of low-level nuclear waste (LLW) sorting at Laurentis Energy Partners (LEP) presents a critical opportunity to improve operational safety, accuracy, and efficiency by minimizing human error and reducing radiation exposure. Through the integration of Industry 4.0 technologies, including wired and wireless communication protocols, detectors capable of interfacing with automation systems, and controllers such as PLCs or Raspberry Pi, we can automate the LLW sorting process in the bin measurement room (BMR) and ensure consistent measurements with repeatability. The potential benefits include streamlining the handling of LLW, reducing worker exposure, and improving data collection through digitalization and automation.

While this section has laid out the key components—detectors, communication methods, and controllers—necessary to build an automated system, the next section will discuss the actual implementation of these technologies. This will include how they will be integrated into a functional apparatus, how the Human-Machine Interface (HMI) will be designed using Node-Red, and the step-by-step approach to automate LLW sorting in practice. By understanding both the technical components and their application, we can develop a robust system that improves both safety and operational efficiency at LEP.

Chapter 3.0: Low-Level-Waste Measurement Automation Apparatus Design

3.1 Introduction

Nuclear energy produces a variety of nuclear waste, apart from depleted nuclear fuel. Nuclear waste in the form of depleted waste makes up only a fraction of the total waste produced, as shown in

Figure 1 A Visual Representation of the different types of nuclear waste in percentage (Radioactive Waste Management - World Nuclear Association, n.d.-b)

, which provides a detailed breakdown of the different types of nuclear waste. **Low-level waste (LLW)**, which accounts for over 90% of the total waste generated, includes a wide variety of items that are often highly variable in size and require delicate handling. LLW consists of scrubs, wires, tools, containers, or any item exposed to radiation, whether from a nuclear facility, power plant, or medical diagnostics.

Not all waste arriving at Laurentis Energy Partners (LEP) is radioactive; some waste contains surface-level contamination that can be wiped off. This occurs when a radioactive particle has settled on an item, causing it to produce emissions. Even small surface contamination can pose environmental and human health risks, requiring careful treatment. Proper handling ensures these contaminated objects are not improperly disposed of in waste facilities.

The motivation for automating the sorting and handling of LLW arises from the need to improve safety, accuracy, and efficiency in waste management. Manual processes, though effective, are time-consuming and involve significant human interaction, increasing the risk of radiation exposure. Automation offers a pathway to reduce human exposure, increase the precision of radiation measurements, and speed up the sorting process. This shift to automation necessitates meeting specific design requirements, which are outlined in the following section.

3.2 Design Requirements

The device in design must be able to satisfy certain requirements that will enable to improve LEPs process. The design requirements are derived from the suggested improvements mentioned by Techbasics during their evaluation of LEPs facility as mentioned in the introduction of the thesis. The requirements have been appropriately selected to reflect the recommendations of Techbasics but enable it by designing an apparatus to do them. The design requirements are as follows:

1. Minimize human interaction with radioactive materials to limit radiation exposure. Automation is critical to reducing worker contact with LLW and ensuring a safer environment in LEP's facilities.
2. Enhance accuracy in radiation measurements for gamma and tritium emissions. The system must provide precise, consistent data without the variability introduced by manual measurement methods.
3. Enable repeatability of the measurement process to improve accuracy and consistency of measurements specifically for gamma and tritium radiation. The system should be able to read the same bag multiple times and provide a similar result.
4. Enable scalability to support future needs. The design must be modular, allowing for the easy addition of new detectors, technologies, and capabilities as LEP’s waste management demands grow.

5. The Apparatus must be built for demonstration purposes in a cost-effective method to be able to prove that automation can indeed help LEP.

With these design goals in mind, the following technical requirements outline the specific functionalities the apparatus must achieve to ensure it meets LEP's operational needs.

3.3 Technical Requirements:

The technical requirements are determined based on the design requirements and provide a detailed breakdown of milestones the apparatus needs to achieve to meet the overall design goals. These technical requirements specify how the apparatus will operate and outline the necessary functionality. There are several key technical requirements that the design must meet to ensure it fulfills the broader design objectives. These include:

1. The apparatus must be capable of measuring radiation levels using gamma and tritium detectors, the detector selection needs to be flexible as the detectors used can change based on availability. This includes gamma and tritium measurements

2. The system should be able to **weigh waste bags** as this data is crucial for proper waste classification and handling. The weighing of the bags is an estimate to how heavy the contents of the bag are and does not need to highly accurate as this is intended for the BMR room. The sorted wasted by the workers will get weighed in detail at a later point in LEPs overall process from the earlier section.

3. The automation system must be able to generate QR codes for an arriving bin once deemed safe to sort. This allows each of the bags to receive a unique ID for later parts of LEPs processing helping workers identify the emissions of the contents of the bag.

4. The apparatus must be able to support any form of serial and analog communication as this is crucial of the scalability aspect of the apparatus as mentioned in the functional requirements.

5. The apparatus must be able to be controlled remotely such that workers can control the device remotely within the BMR or externally. Additionally, the values being measured by the apparatus must be visible live for workers to see if there are measured radiation spikes which may not be represented in the average.

6. Lastly the apparatus must be designed in a way allowing for future improvements to be implemented with ease and allowing for scalability. Scalability refers to the ability to have multiple different apparatus operating from a single control interface.

With these technical requirements established, the following section provides an overview of the integrated systems designed to meet these goals.

3.4 Design Overview

The Low-Level Waste (LLW) apparatus consists of several integrated systems that depend on each other to achieve the automation process. Figure *25* below illustrates the three primary stages of design.

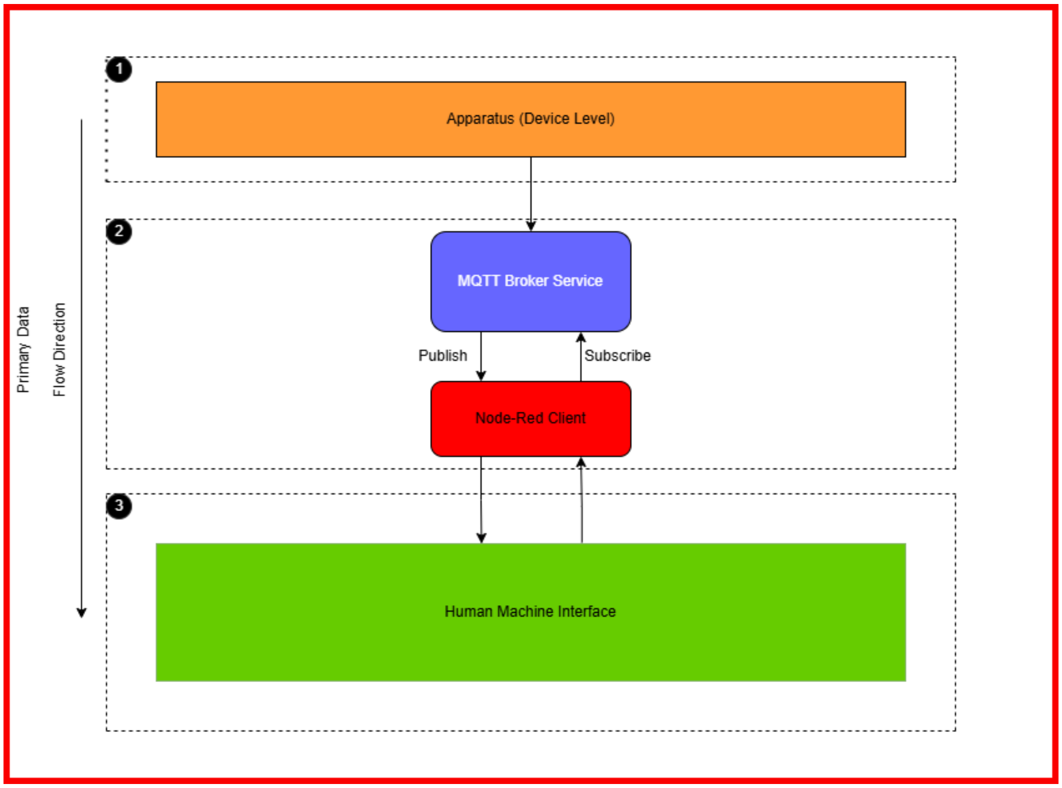

Figure 25 High level break down of design

1. **Apparatus (Device Level):** This physical aspect of the apparatus is where LLW bags are to be placed, and data collection occurs for key measurements such as weight, gamma radiation, tritium levels, and bag identification occurs. The apparatus is designed as a box form factor that allows items to be placed inside for measurement. It includes three key features: weight scale, gamma and tritium sensors, a rotating base and houses the QR code scanner and microcontrollers for automated bag identification. These components are essential for the functionality and scalability of the system, allowing the apparatus to meet the requirements set.

2. **Software (Communication Layer):** This system facilitates communication between the apparatus (System 1) and a remote device (System 3) using MQTT protocol. This allows

the devices to communicate wirelessly over Wi-Fi, even if they are on different networks. This communication system ensures that data is seamlessly transmitted from the apparatus to the remote device, where it can be controlled and monitored.

3. **Human-Machine Interface (HMI):** The HMI system is the user interface for operating the apparatus. Located in the receiving tent, the HMI allows users to control individual devices or all devices simultaneously, simplifying the control and operation of the apparatus. It provides the essential tools for managing the system and streamlines the user experience.

In the following sections, a deeper analysis of each of these systems will be provided, along with the design process and integration of their components.

3.5 Apparatus Design (System 1)

3.5.1 Physical Apparatus Construction

3.5.1.1 Construction of Apparatus:

The apparatus is primarily constructed from aluminum rails and hardboard. The top and side panels are made from clear plastic (plexiglass), while the bottom is made from hardboard reinforced with wooden planks for added support. The rotating base components are 3D printed, ensuring a lightweight and cost-effective solution. The size of the apparatus was determined based on the observed size of bags found in the bins located in BMR. This was based on a qualitative observation made at LEPs facility. Figure 29 illustrates the apparatus that was built as a part of the design process.

3.5.1.2 Placement of Detectors:

The gamma sensor and tritium detectors, provided on loan for testing purposes, are not permanently mounted to the apparatus. These detectors are utilized only for testing phases and can be easily integrated and removed as needed for different measurement activities, such as gamma and tritium measurements. The ideal placement of detectors is identified in Figure 28 in red text as well as where the detectors should be placed to ensure full coverage of the emissions from the contents of the LLW bag. The ideal placement allows a full scan of the bags to be obtained as the base rotates and the detectors log the measurements. Integrating 3 detectors ensures that as much surface area of the bag is measured as possible.

3.5.1.2 Linear Actuator:

The linear actuator is mounted at a 45-degree angle using a 3D-printed mount. This angled positioning optimizes the actuator's performance and ensures that the bag can be pierced without shifting the bag within the apparatus. The extended length of the actuator was accounted such that when fully extended it does not apply pressure to the weight scale below. The intent of the linear actuator in the design is to penetrate the bags of waste to capture the tritium concentration. Figure *28* below shows the 3D-printed mount and the linear actuator integrated into the apparatus.

3.5.1.3 Rotating Base with Scale Integration

The rotating base is constructed from a hardboard, and all surrounding components and mounts are custom 3D printed to achieve the rotational motion.. The base integrates the weight measurement components such that you can continue to accurately measure the weight while the base is rotating. Figure 26 and Figure 27 demonstrate the integration between the motor in the center in Figure *26* and the scale components surrounding it. The base where the LLW bags rest is attached using a coupling system such that the force of the bag is not passed to the motor but to the scale components. A detailed analysis of the components is shown in Section 3.7.

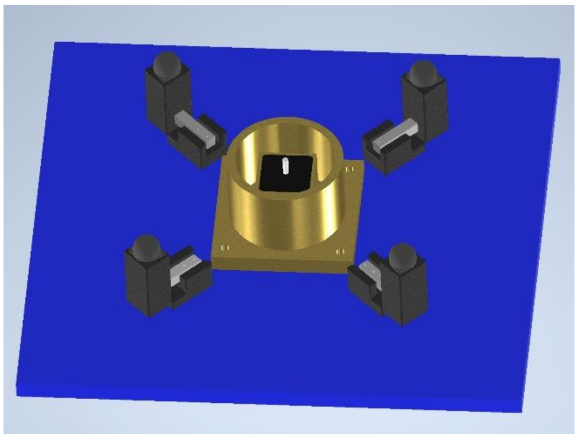

Figure 26 Top View of Rotating Base with Scale

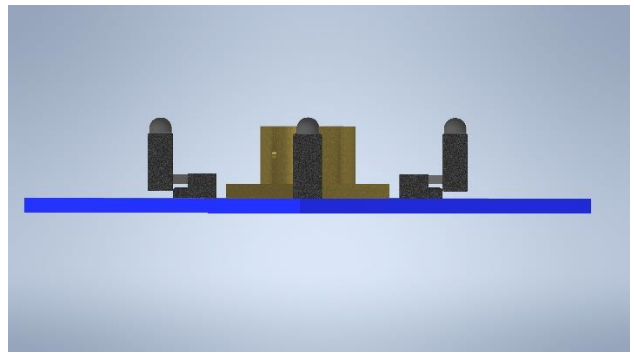

Figure 27 Side View of Rotating Base with Scale

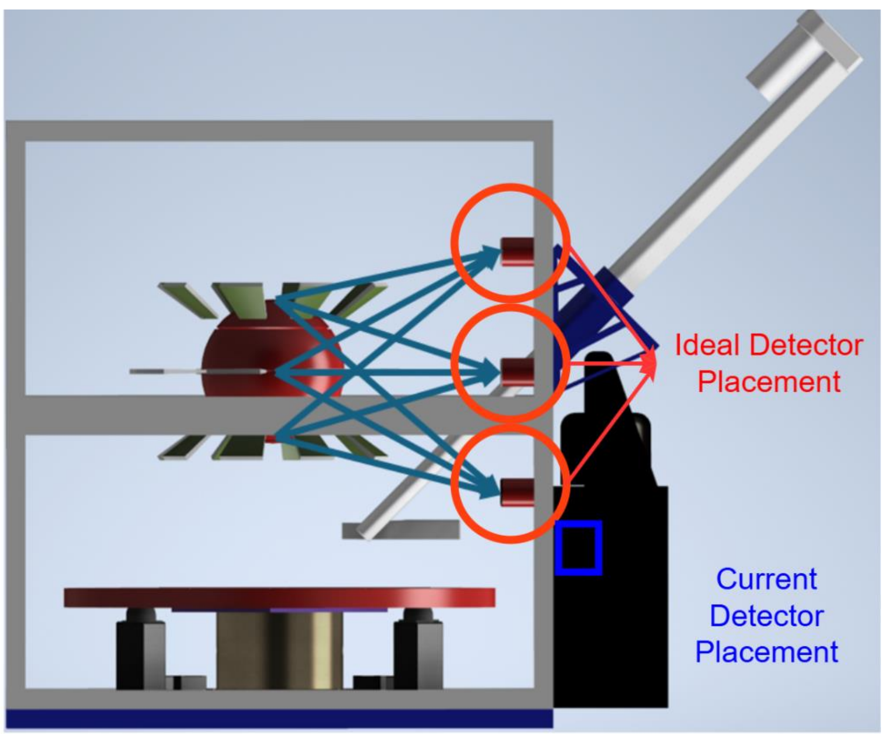

Figure 28 Detector Locations on Apparatus

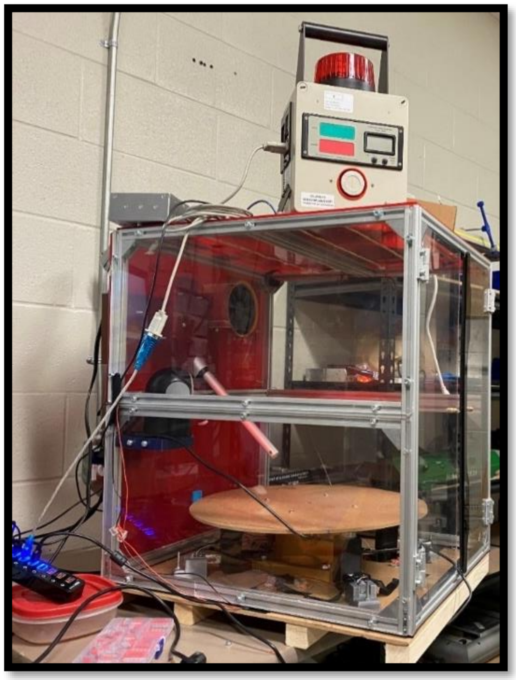

Figure 29 Prototype Apparatus Built

Now that we have seen the general apparatus that is built, we will now move on to parts that make up the apparatus.

3.5.2 Gamma and Tritium Detectors:

This section discusses the process of gamma and tritium detector selection. It was based on three factors:

- Detectors that are used at LEP facilities.
- Detector availability.
- Serial communication capability.

3.5.2.1 Detector Radiation Measurement Accuracy Test

As seen in Chapter 2, many suitable detectors were investigated. A test was conducted to measure the detection accuracy of detectors currently used at LEP. All detectors tested were first checked by ensuring that they provided the same reading in background radiation. A bag was selected from the receiving tent as a control, and within the bag a specific location was selected. The detector being tested was first allowed to read the accepted value in background radiation, then tested with the bag. The detector was then allowed to settle down in background radiation and tested once again. The same procedure was used for all detectors. The test was completed with two radiation values as shown in Table 5 below.

Table *5* Gamma Detector Testing

Detector	Type of Detector	Source A	Source B
Control		$0.55\frac{\text{mSv}}{\text{hr}}\ (55\frac{\text{mRem}}{\text{hr}})$	$5\frac{\text{mSv}}{\text{hr}}\ (500\frac{\mu\text{rem}}{\text{hr}})$
RDS-31iTx	GM	$0.3-0.33\ (30-33)$	$\cong 5\ (500)$
Tyne Model 7043	GM	$0.3-0.33\ (30-33)$	N/A
Bot Engineering RM-P1000	GM	$0.3-0.33\ (30-33)$	N/A
Canberra	Scintillator (NaI)	N/A	$4.5 - 5\ (450-500)$
P200	GM	$0.5-0.55(50-55)$	$11\ (1100)$

Results for 55 $\frac{\text{mRem}}{\text{hr}}$:

- BOT Engineering P200 did favourable in this test providing a read of $0.5 - 0.55\,\frac{\text{mSv}}{\text{hr}}\left(50 - 55\,\frac{\text{mrem}}{\text{hr}}\right)$.
- The RDS=31iTx read $0.3 - 0.33\,\frac{\text{mSv}}{\text{hr}}\ \left(30 - 33\,\frac{\text{mrem}}{\text{hr}}\right)$ failing this test.
- Tyne Model 7043 also read $0.3 - 0.33\,\frac{\text{mSv}}{\text{hr}}\left(30 - 33\,\frac{\text{mrem}}{\text{hr}}\right)$ failing the test.
- Bot engineering RM-P1000 read $0.3 - 0.33\,\frac{\text{mSv}}{\text{hr}}\left(30 - 33\,\frac{\text{mrem}}{\text{hr}}\right)$ also failing the test.
- Canberra was not configured correctly and did not read past 10mrem due to the software limit that was not known at the time of testing and was not tested again due to it being on loan.

This concludes the testing for Source A outcomes from Table 5.

Results for $500\,\frac{\mu\text{rem}}{\text{hr}}$:

- RDS-31iTx performed desirable under these doses; the values read from this detector matched those of the control detector values.
- P200 performed desirable, but the value that it was reading was significantly higher than that of the control and the RDS-31iTx, it read $10\,\frac{\text{mSv}}{\text{hr}}\left(1000\,\frac{\mu\text{rem}}{\text{hr}}\right)$, which is unusual as no other detector reported this reading.
- The Canberra Gamma spectrometer performed favourable as well, reporting a reading of $450 - 500\,\frac{\mu\text{rem}}{\text{hr}}$. This detector has a detachable probe that can be separated from the main body.

- The Tyne detector failed this test as due to its size an optimal placement was unable to be obtained in a way that would read the values for this test; it was not useful.
- The Bot Engineering RM-P1000 was not tested in this scenario due to the availability of the detector at the time. This concludes the testing for Source B outcomes from Table 5.

Summary of Findings:

- The BOT Engineering P200 and Canberra Gamma Spectrometer showed favorable results overall, though the P200 produced abnormally high readings in one test.
- The RDS-31iTx performed well at lower radiation levels (500 µrem/hr) but failed at higher doses (55 mRem/hr).
- The Tyne Model 7043 and BOT Engineering RM-P1000 struggled to provide reliable data under both test conditions, indicating issues with their placement or calibration.

3.5.2.2 Gamma Detector Selection

In the receiving tent, LEP's preferred detector is the BOT Engineering P200. BOT Engineering was the most cost-effective when requesting estimates from detector manufacturers because it has an established relationship with both LEP and McMaster University. This longstanding collaboration allowed us to secure a loan for the AR600 detector in the shortest time frame.

The AR600 supports serial output for reading detector points and is compatible with the same detectors currently in use at LEP. Since these detectors have already been approved for use in the receiving tent by LEP, this saved valuable time, as there was no need for additional verification to meet LEP’s requirements.

Since it used the same detector as the P200, the AR600 did not undergo as much testing as other detectors; yet it is the preferred detector. This is primarily made possible by BOT Engineering's prompt response and ability to lend the detector. Its slower polling rate and the delay in showing information on its digital screen are some of its disadvantages. Considering these drawbacks, the AR600 was still chosen due to its availability. The AR600 satisfied all three criteria for detector selection, detectors used by LEP, and availability of detectors, and providing serial communication support.

3.5.2.3 Tritium Detector Selection

There were only two tritium detectors that LEP uses, and out of the two, the Tyne 7043 was selected. It was the only one that can send measurements to a computer via serial communication. The Tyne detector is considered slower than the Overhoff Model 200. The Overhoff model does not support serial communication, but there is a version that does. Since the Tyne was readily available at LEP and supports serial communication, it was selected. The Tyne 7043 detector can also take gamma measurements. Since the gamma detector that is selected only supports one detector at a time, values of the Tyne can also be used to demonstrate a scenario where there is more than one gamma detector in the apparatus. The Tyne 7043 satisfied two of the three criteria for detector selection, serial, and availability of detectors.

With the selection of the tritium and gamma detectors complete, we now focus on the weighing system, which plays a critical role in ensuring accurate measurements during the 360-degree scan.

3.5.6 360˚Rotating base and Weighing System:

3.5.6.1 Rotating Base:

To design the rotating base, the minimum design load of 20 kg and 21 kg including the plate is used. To rotate the circular base, there is the minimum requirement that the motors would need to satisfy. Below is the calculation that will help determine the required torque needed from the motor:

$$\alpha = \frac{\Delta\omega}{\Delta t},$$

$$I_{cm} = \frac{1}{2} mR^2$$

$$m = 21 \text{ kg}$$

$$\omega_f = 0.20943951 \frac{\text{rad}}{\text{s}} \text{ or } 2 \text{ rpm}$$

$$\omega_0 = 0$$

$$\Delta t = t_f - t_0 = 1 \text{ sec (This indicates that the final speed of the apparatus should be obtained in 1 sec.)}$$

$$I_{cm} = 0.5 \times 21\text{kg} \times 0.25^2 = 0.65625 \text{ kg} * \text{m}^2$$

$$\alpha = \frac{\Delta\omega}{\Delta t} = \frac{0.20943951 \ \frac{\text{rad}}{\text{s}}}{1 \text{ sec}} = 0.21 \ \frac{\text{rad}}{\text{s}^2}$$

$$\tau = I\alpha = 0.65625 \text{ kg} * \text{m}^2 \times 0.21 \frac{\text{rad}}{\text{s}^2} = 0.0901 \text{ Nm} \cong 0.1 \text{ Nm}$$

Therefore, the motor must have a starting torque of at least 0.1Nm to rotate this body of mass at the required 2rpm.

Since the motor motion is tied to the gamma detector's ability to poll data, we get one data point every second (Polling rate of AR600 using serial communication). To rotate the mass 360° would mean that it would take 360 points in 6 minutes, which is considered slow. A test was conducted that checked the response rate of the detector, and the detector can respond to high gamma counts in about 2 seconds, or 2 points.

To ensure that the measurements are done in 30 seconds, this would mean that the base would have to rotate $\frac{360}{30} = 12°$ per point. This would mean that we get 30 points per rotation, which is satisfactory for the BMR as they only need to know the maximum gamma count per bag and is not intended for concrete measurements.

Based in the calculation performed, a stepper motor was selected, as they are pre-categorized by stall torque (0.1 Nm), making selection straight forward. As indicated by the calculation, the motor needs to be able to have a starting torque of 0.1 Nm while being able to control the rotation of the motor. Stepper motors are classified by frame sizes. The size dictates the step angle and holding torque, which are key parameters when stepper motors are being selected. Stepper motors require a driver, which interfaces between the controller, power, and motor. Stepper motors are known for their measurement of holding torque. This is because a stepper motor takes steps instead of a continuous rotation to get the precision required. The holding torque indicates the torque the motor has going from one step (0.1 Nm) to another step. This is ideal for the calculation, as I am using the mass the most must spin to calculate the torque, as seen in the calculation above.

Now that the motor is selected based on the torque requirements defined, attention turns to the load cell selection, which is critical for weighing the LLW bags during the rotation process.

3.5.6.2 Load Cell Selection:

The scale selection for the apparatus is determined based on data provided by LEP, which comprised the weights of all bags handled by LEP until January 2022. A histogram shown in Figure 30 was generated using data from over 52,000 bags, revealing that the largest frequency of weights is between 0 and 10 kg, with the most common range being 2-4 kg and a peak occurrence of over 2,500 bags ranging between 3-3.5 kg. While the majority of bags are in the 2-4 kg range, there is a notable number of bags in the 10-20 kg range. Given this wide distribution, a 20 kg load cell was selected to cover the entire weight range. Load cells are available in 1 kg, 3 kg, 5 kg, 10 kg, and 20 kg capacities, but choosing anything below 20 kg would not accommodate the full range. While the trade-off of selecting a 20 kg load cell is reduced accuracy in the lower weight range, this is acceptable at this stage in LEP's process; the weight is primarily used to flag potential issues for downstream workers, as the bags will be sorted and repackaged later. As a result, the 20 kg load cell was determined to be the best option for this apparatus.

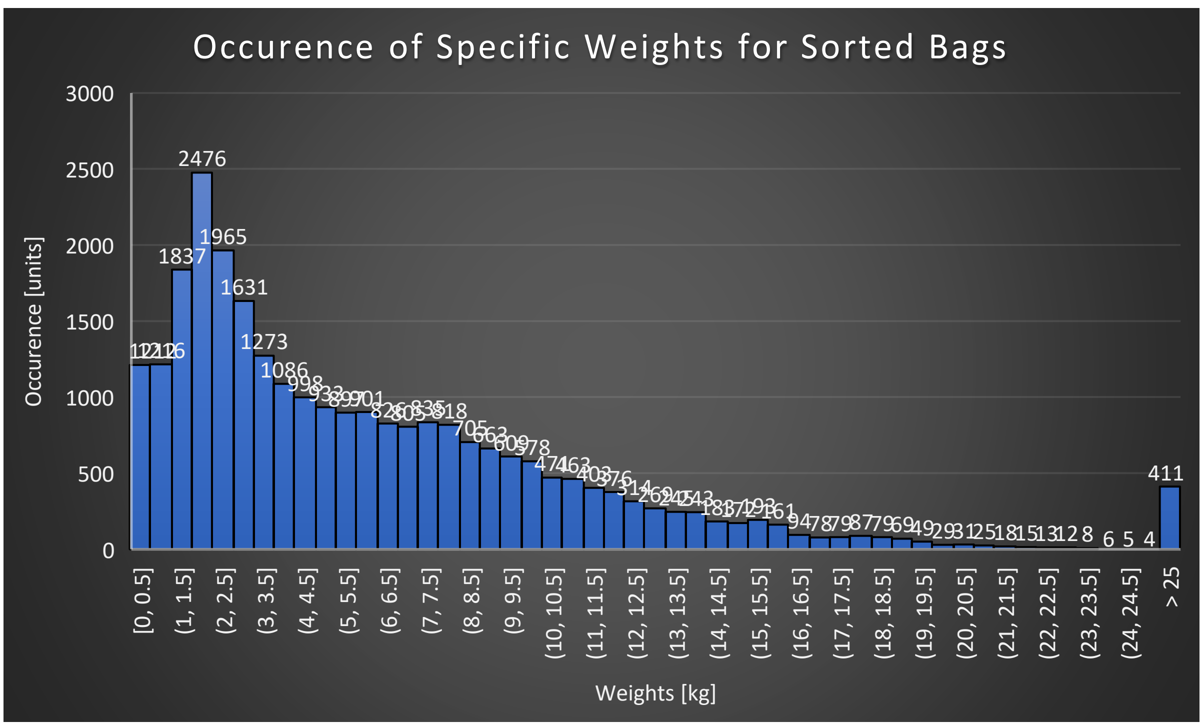

Figure 30 Figure showing the weights of bag that occur at LEP

To enable the bags to rotate for a full 360-degree scan, the scale is implemented into the rotating base of the apparatus as. During the selection process for scales, it was suggested to research load cells. Their compact size and low cost make them an excellent choice compared to digital load cells. The weight measurement system has four load cells and a transmitter, which interprets the readings from the load cell and provides an analog signal. Figure 32 demonstrates how the load cells are incorporated into the rotating base. There are three main parts: horizontal housing allowing the load cell to be mounted. The vertical housing, which applies the load to the cell, activates a Wheatstone bridge circuit. Finally, a low-friction roller that allows for the base to rotate on top of the load cell. Four load cells wired electrically in parallel to measure the voltage. Before the scale can be used to measure the weight, it must be calibrated with known weights and voltage values. The scale is calibrated, accounting for the rotating base to include its weight. Once calibrated, we obtain the following equation.

$$Weight = 2 \times 10^{8}\boldsymbol{x}^{2} - 8 \times 10^{6}\boldsymbol{x} + 80661$$

Where x is the value that is received from the load cells in its unfiltered form. Excel was used to determine the equation, with an R^2 value of 0.98 meaning the equation represents the data from the known weight measurements extremely well.

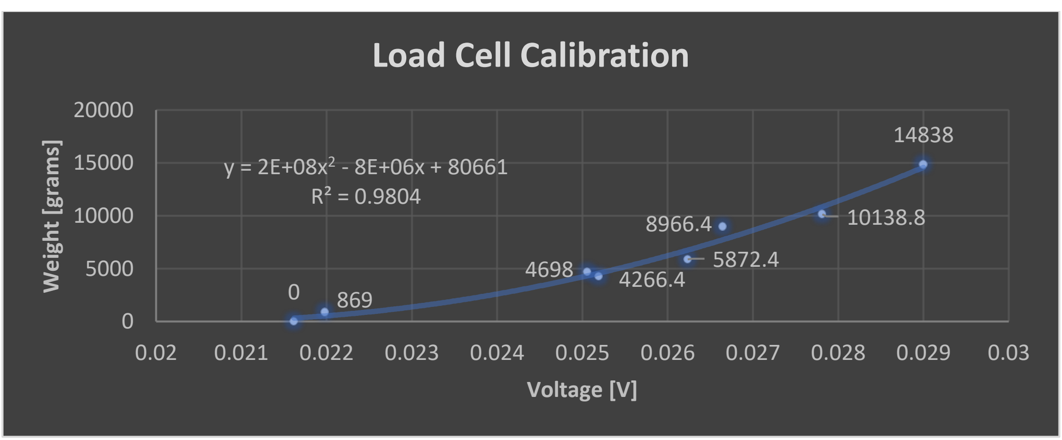

Figure 31 Scale Calibration Curve

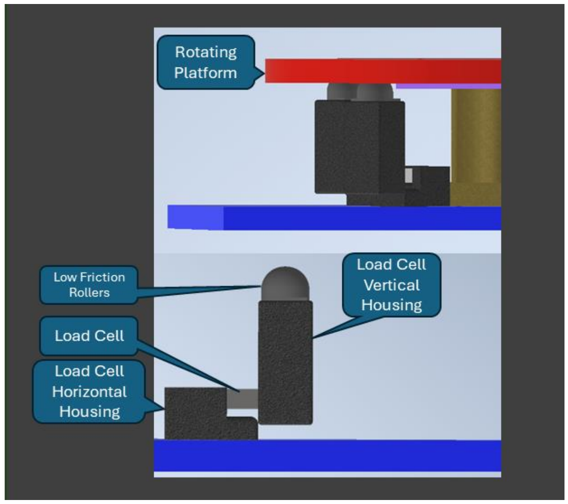

Figure 32 Load Scale Mounts

By combining a carefully selected stepper motor and a 20 kg load cell system, the apparatus can perform accurate 360˚scans while simultaneously measuring the weight of LLW bags, ensuring both precision and scalability in waste handling processes.

To ensure smooth and uninterrupted operation, the design seamlessly integrates the scanning and weighing capabilities, but these functions rely on a hardware and electrical system. This brings us to the next crucial aspect of the apparatus: the hardware and electrical architecture.

3.5.7 Hardware and Electrical Architecture

The hardware and electrical architecture (Figure 33) of the apparatus is divided into three critical sections: Power Supply and Distribution, Data Input and Communication, and Motor and Movement Control. These systems work together to ensure the proper functionality and scalability of the apparatus. The microcontroller is required to ensure all three of these sections can work in harmony with each other to complete the automation to satisfy the design requirements.

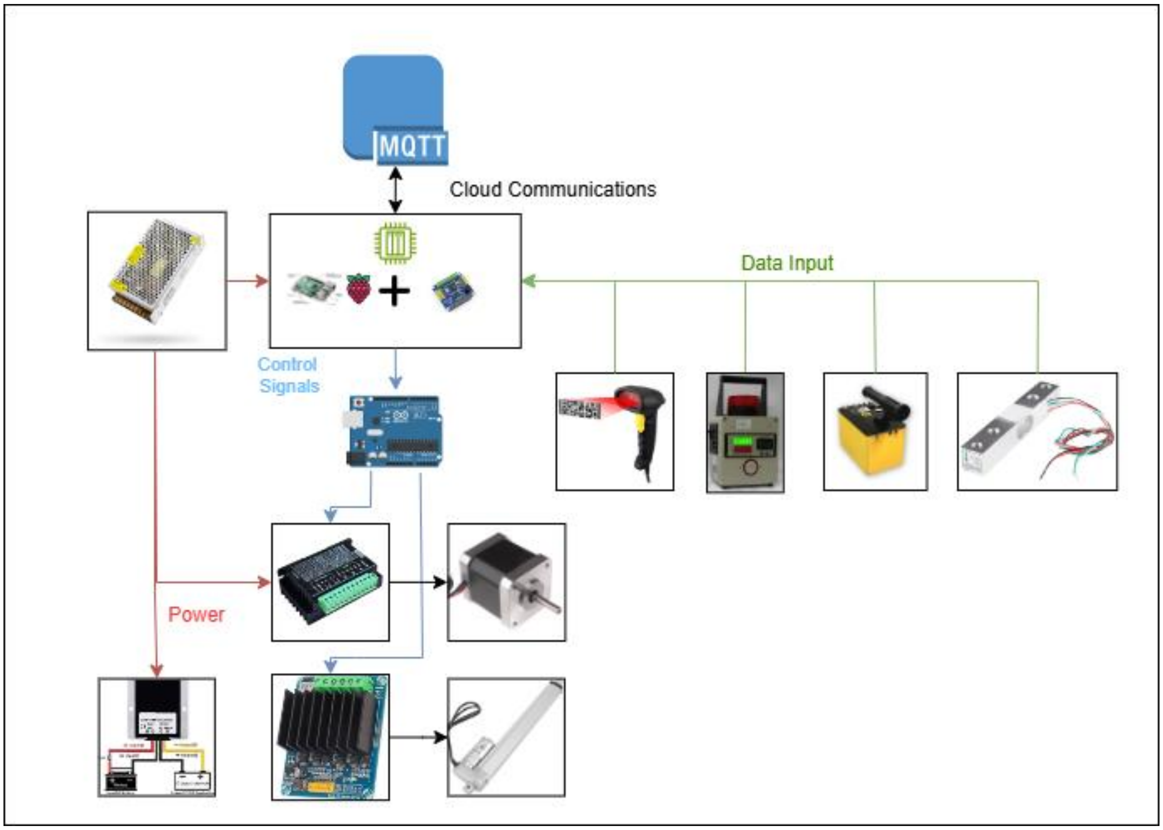

Figure 33 High Level Hardware and Electrical Architecture

3.5.7.1 Microcontroller Selection

Firstly, to understand the hardware and electrical architecture we must first select a microcontroller responsible for executing the automation. After spending time working with both, the controller of choice is the Raspberry Pi. It's more versatile for purpose of the project. The data retrieval using a Raspberry Pi is easier and flexible as it supports Bluetooth, Wi-Fi, and simple USB drives to save the data from the apparatus. Cost wise the Raspberry Pi is cheaper for the functionality it offers. To obtain the same functionality in a PLC, they may cost thousands.

Secondly if someone wishes to continue this project after me a Raspberry Pi is simpler to learn. From research that has been gone into during the detector selection process, for automation controllers such as a PLC to perform their best it is important for the sensors to utilize protocols that can easily be incorporated with a PLC such as MODBUS, Ethercat, and Ethernet IP. These protocols are designed for automation purposes. In the case for this project a CLICK PLC was used to attempt communication between the AR600 which supports serial. Most detectors that have been investigated are not intended to be used with PLCs, they are intended to be used with computers via serial communication. Raspberry Pi supports video integration, and coded program is transferrable to other ARM based microcontrollers such as the Nvidia jetson for advanced video-based recognition.

3.5.7.2 Power Supply and Distribution

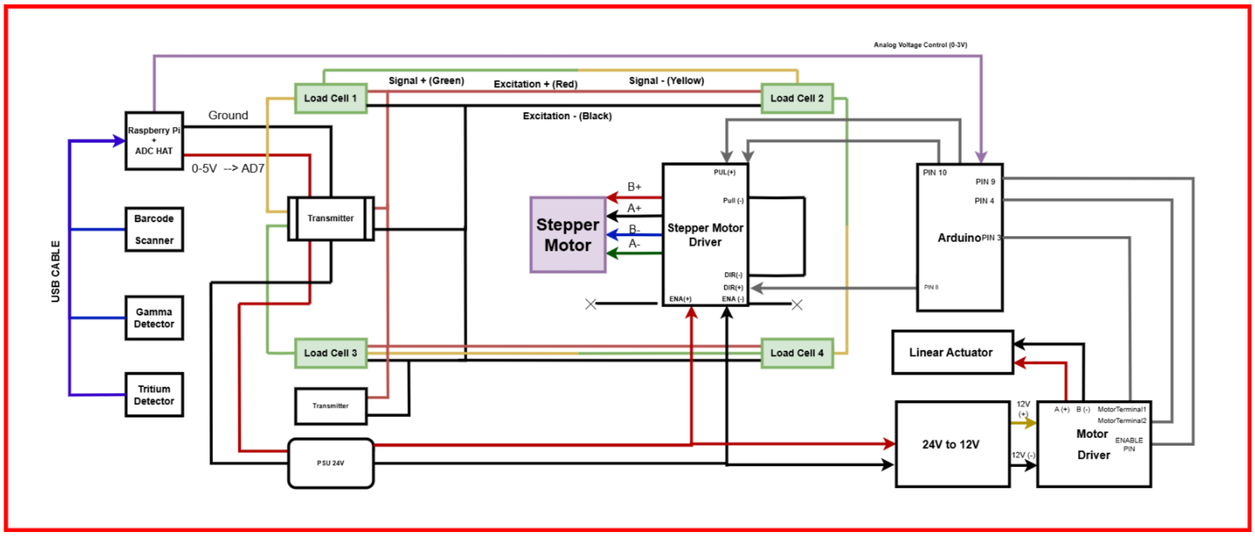

Figure 34 Detailed Electrical Wiring Diagram

The first section is Power. Power is provided to the entire system using a 24V power supply. The power supply provides power to the key components: Raspberry Pi, motor drivers, and detectors if needed (detector-specific). To accommodate the linear actuator which requires a 12V source a step-down power converter enables 24V → 12V. Figure 34 illustrates the detailed wiring diagram required to supply power to the entire apparatus.

The color-coded wiring system simplifies the power distribution:

- **Red/Black**: These wires represent the positive (red) and negative (black) power supply rails. For the load cells, these colors correspond to "excitation" as defined in their respect datasheets.
- **Other Colors**: Different signal rails are shown with various wire colors to facilitate clear communication and functionality. Labels are provided for specific wires to show their significance.

3.5.7.3 Data Input and Communication

The data input system enables the Raspberry Pi to collect values from various sensors and components. These inputs include:

- Detectors: The gamma and tritium detectors communicate via serial communications with the Raspberry Pi, sending data for radiation measurements. USB ports on the Raspberry Pi are used to facilitate the connections as seen in Figure 35 (*Meet Raspberry Pi | Getting Started with Raspberry Pi | Coding Projects for Kids and Teens*, n.d.). The Raspberry Pi communicates with the detectors using serial communication via com port. Tyne 7043 and BOT Engineering AR600 have serial outputs, both needing a different connector but following the same protocol. AR600 utilizes a baud rate (the speed at which data is transmitted between devices) of 9600 bps, determined based on the detector datasheet. AR600 utilizes an RS 232 protocol using a DB9 connector (*Figure 36* (*Amazon.Com: SABRENT USB 2.0 to Serial (9 Pin) DB 9 RS 232 Converter Cable, Prolific Chipset, HEXNUTS, [Windows 11/10/8.1/8/7/VISTA/XP, Mac OS X 10.6 and Above] 2.5 Feet (CB-DB9P) : Electronics*, n.d.)). Tyne 7043 uses the same RS232 protocol but utilizes a different connector, a circular DIN based connector (*Figure 37* (*Amazon.Com: Teykst 6 Feet USB to*

Mini Din Serial Adapter Cable with FT232RL Chipset, 8 Pin Male Connector, for Yaesu Radio Compatible, CT-62 CAT Audio Interface Cable : Electronics, n.d.)).

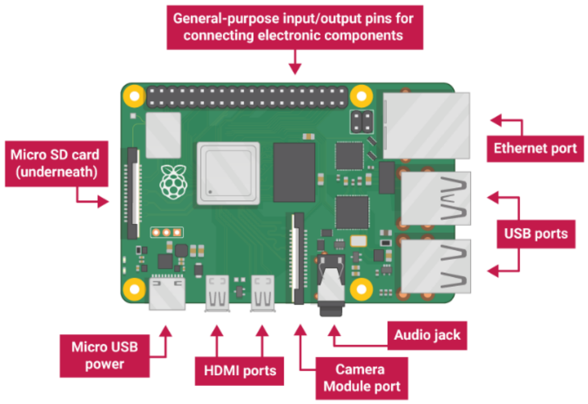

Figure 35 Raspberry Pi Port Descriptions

Figure 36 Serial (9 Pin) RS232 to USB

Figure 37 Serial (DIN 8) to USB

- Load Cells: The weight of the bags is measured by the load cells using analog DC voltage measurements, which are converted into weight values. The load cells require a transmitter which amplifies the signals and converts it to a voltage that can be interpreted by a computer. A AD/DC hat is used with the Raspberry Pi to interpret the values from the load cells.

- Additional data input devices, such as QR scanners for bag identification, can be connected as needed using the provided USB ports on the Raspberry Pi or using the GPIOs.

3.5.7.4 Motor and Movement Control

The Arduino is responsible for motor control. The Arduino was included in the design because it supports 5V analog communication and has dedicated pulse width modulation (PWM) outputs, which are essential for controlling motor drivers. Each motor in the system requires its own driver. The stepper motor is controlled by a stepper motor driver, which regulates its direction and speed. The Arduino is connected to this driver to manage the motor's rotation. Additionally, the linear actuator is controlled via an H-Bridge, which extends the actuator. The H-Bridge is also connected to the Arduino, allowing for seamless integration of motor control. The Raspberry Pi utilizes a Waveshare High-Precision AD/DA Board Figure 38, which allows for reading analog voltages and sending analog voltages between 0V and 5V to and from the Arduino.

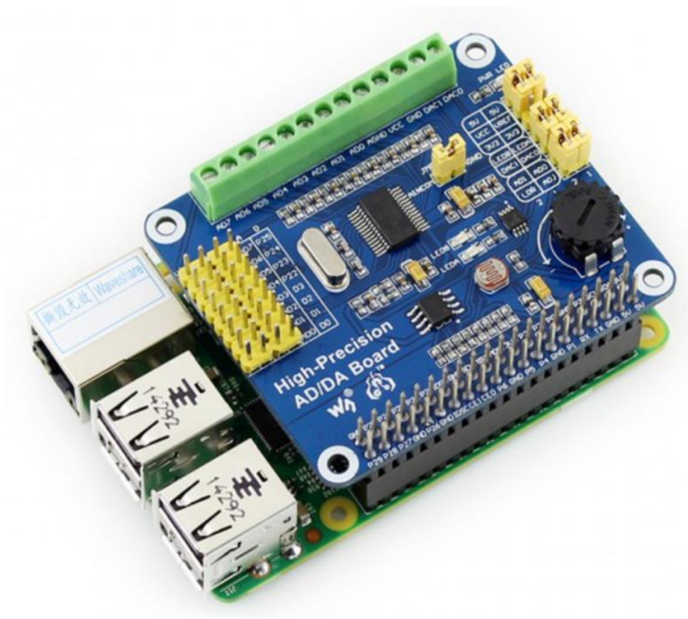

Figure 38 Waveshare High-Precision AD/DA Board

Now that we have discussed the electrical aspect of the apparatus, now we must discuss the design of the software architecture which allows the hardware to work together on the request of automation.

3.6 Software and HMI Design

The software architecture is split into two sections, the communication layer, and the HMI. Figure 39 illustrates how the software Architecture plays a role in the overall LLW Automation Apparatus.

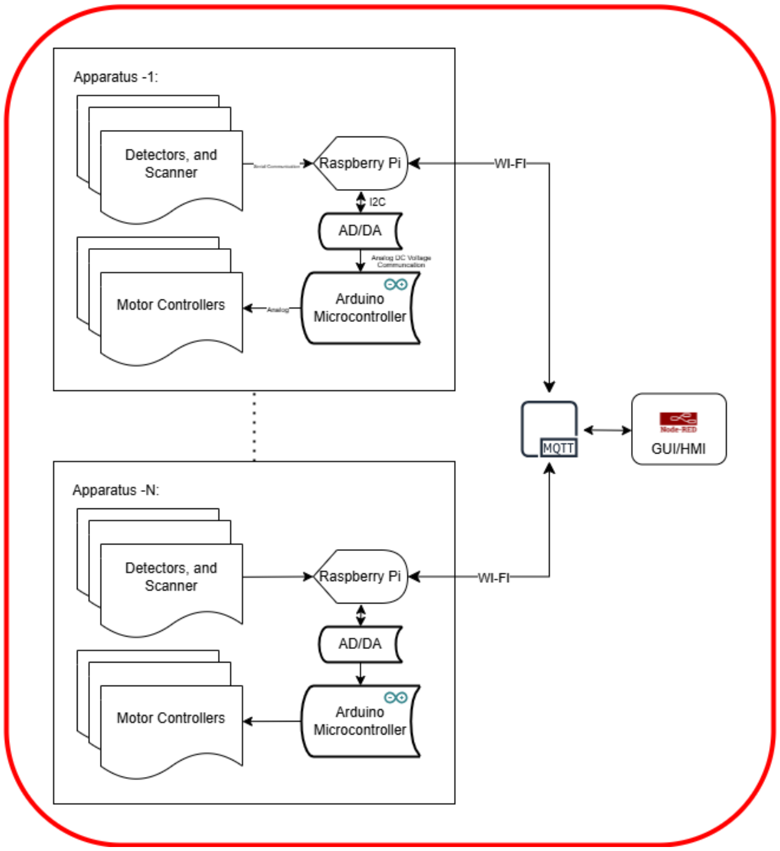

Figure 39 Software Architecture Breakdown

3.6.1 Communication Layer

The communication layer is responsible for managing the data transfer that occurs between the apparatus (Raspberry Pi) and the HMI. The goal of the communication layer is to ensure that a seamless communication is provided over the network to enable remote use of the apparatus.

3.6.1.1 Communication Protocol Selection

Although the Raspberry Pi can be considered a computer, it was utilized in the apparatus as a microcontroller to manage automation tasks. MQTT and local Wi-Fi communication via UDP socket communication are two methods that were explored. Both allow for sending and receiving data over Wi-Fi. For UDP, a.NET-based application Figure 40 was developed to receive data from the Raspberry Pi.

UDP development was halted as network issues at McMasters, prevented me from accessing the local network. This prevented any data transfer from one device to another. While UDP was the ideal choice, it was ultimately abandoned as the local network policy prevented further development at McMaster resulting in MQTT being selected. It provides similar functionality and is well integrated with Node-RED, making it a more practical choice. MQTT is simpler to learn, which is beneficial if the project is handed off to another student.

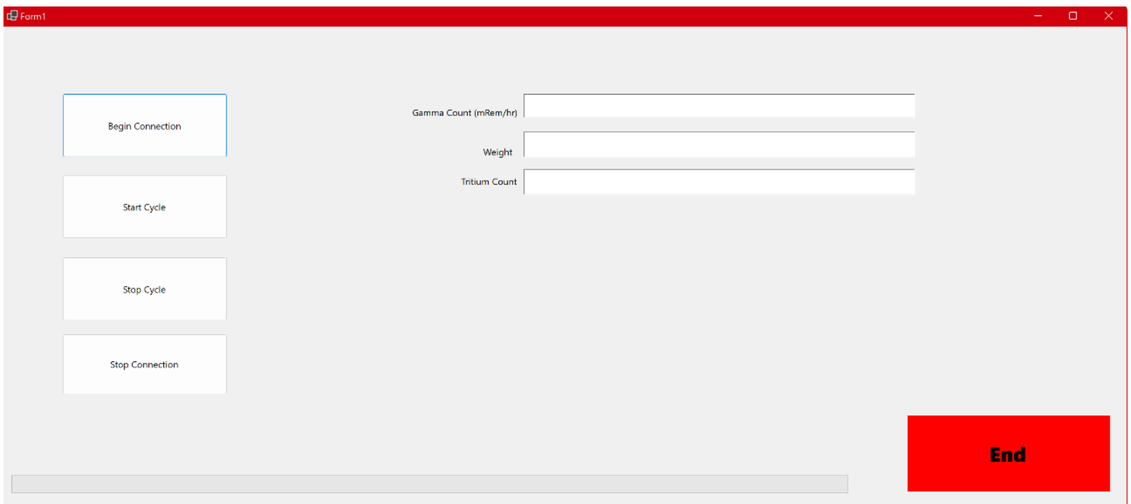

Figure 40 .NET Based Application

3.6.1.2 Software Architecture

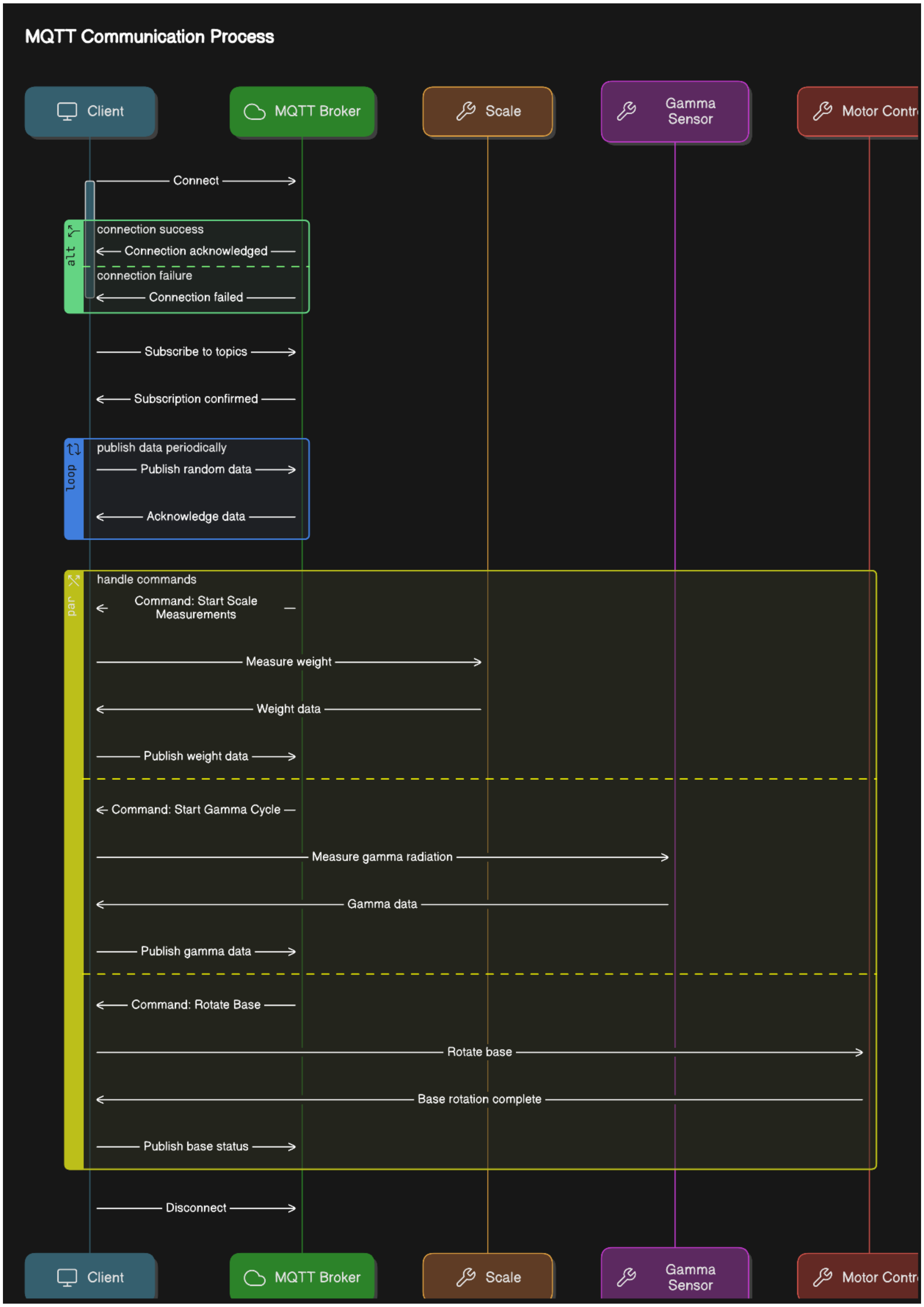

Figure 41 Detailed Software Flow between Cloud Based Node-Red HMI and Apparatus

Figure 41 shows a visual of the communication layer indicating the data requested by the client and the data received back from the apparatus and its different detectors and functions. There are three steps that are show:

- Green Section: This section indicates the connection establishment between the Node-Red Interface (cloud based) and the apparatus functions. The functions are identified at the top and bottom of Figure 41.
- Blue Section: This section is responsible for publishing the data to the apparatus and fetching data from the apparatus. This is the main form of communication between the apparatus and HMI.
- Yellow Section: This section is responsible for checking the incoming data from the HMI and executing the appropriate automation function or sequence.

The software architecture manages communication between Raspberry Pi and the HMI. The Raspberry Pi runs a Python program that handles incoming data and executes tasks based on HMI inputs. For example:

- When the user initiates gamma measurement, the Python program opens the communication port, collects readings for 30 seconds, and sends real-time data back to the HMI via MQTT. A flow chart on how the software works is shown in Figure 42. The other respective functions work similarly.

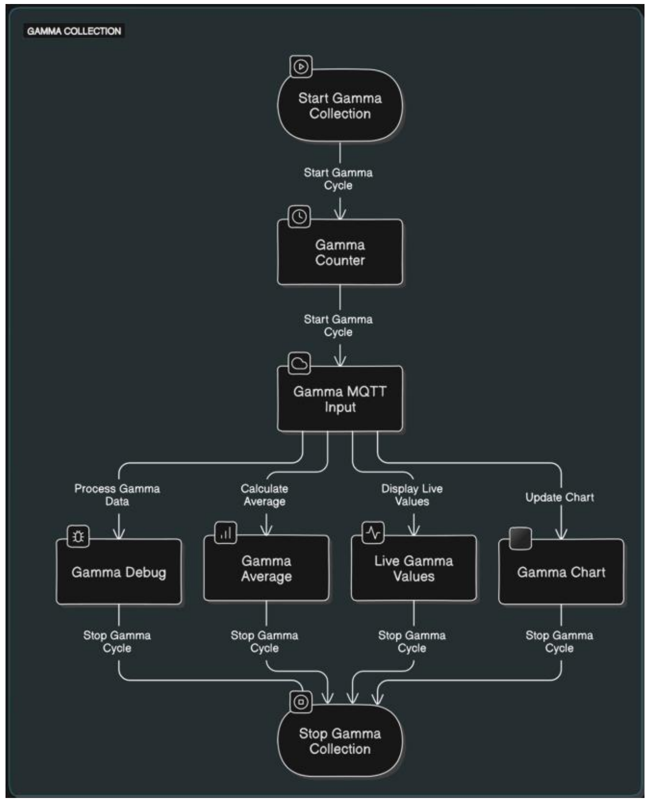

Figure 42 Gamma Measurement Function Node-Red

- Similarly, the motor control functions are triggered via AD/DA communication. When a motor-related function is called, the Raspberry Pi sends a signal to the Arduino, which then activates the respective motor driver. Figure 43 represent the detailed software flow that enables the motors to be driven. In this implementation the base rotation is left on indefinitely, when a request to extend the arm or retract the arm is initiated the rotating base is disabled. The interrupt is an analog signal that is received from the Raspberry Pi using the AD/DA hat.

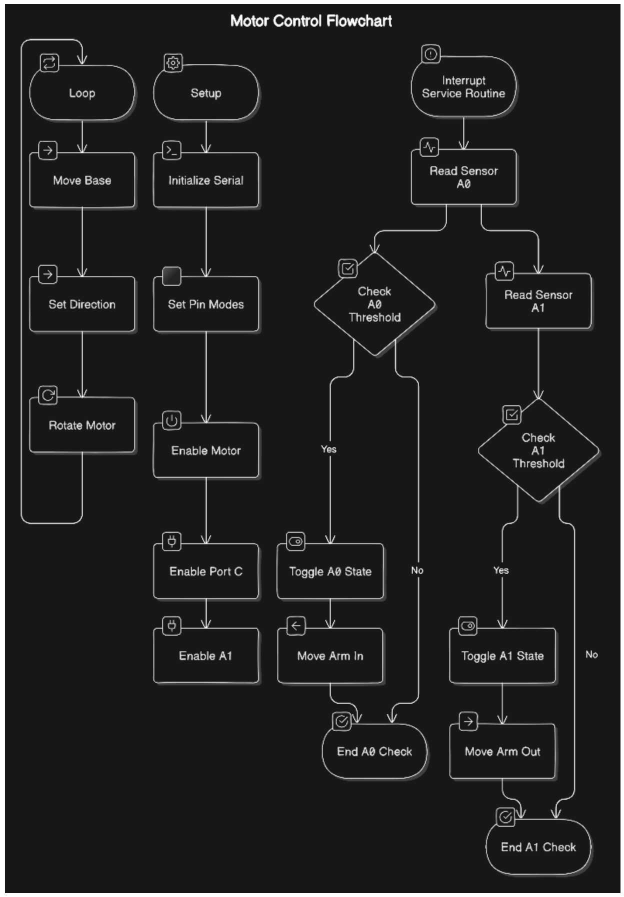

Figure 43 Motor Control Software Flow

The communication between Raspberry Pi and HMI does not require them to be on the same network, further improving the system's flexibility.

3.6.1.3 Object Detection for Bin IDs

QR Code Recognition was implemented for bag identification as mention in the technical requirements. It was implemented using two different methods: a camera-based approach and a scanner-based approach. The camera-based approach shown in Figure *45* used Python to use one or two cameras to detect the QR code and decode its value. Python threading and CV2 (computer vision) libraries are used to implement decoding functionality. Each camera was executed with its own thread, allowing them to be executed simultaneously, but followed the same function to interpret the QR code, allowing fast decoding of the QR code. When implementing this method on the Raspberry Pi, the system lacked computational power with the rest of the code, scraping the implementation.

The second implementation was simpler; it used an off-the-shelf barcode scanner and returned value. The downside being that the Raspberry Pi interpreted this scanner as a HID device, providing no control when the scanner is accessed. The purpose of the QR code is to track the bags that are tracked.

In both methods QR codes need to be generated based on the bin name by LEP either manually or using a code. In the case for this thesis a python code was created to create QR codes based on the bin name with 100 iterations for each bin. The naming nomenclature was observed in LEPs tracking spreadsheet. Figure 44 shows the QR code generation flow for creating QR code for bags for identification purposes. The naming scheme used is: [Bin Name]-[0→100] creating 100 unique ID based on bin name.

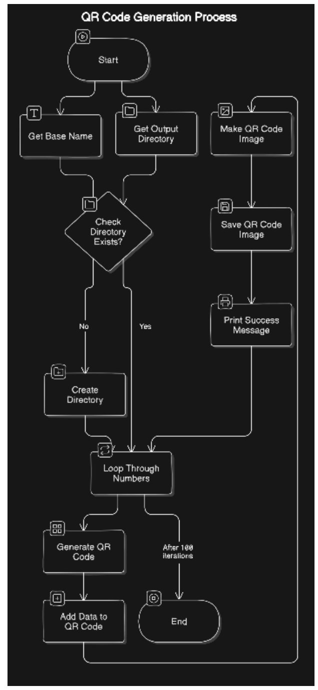

Figure 44 QR Code Generation Process

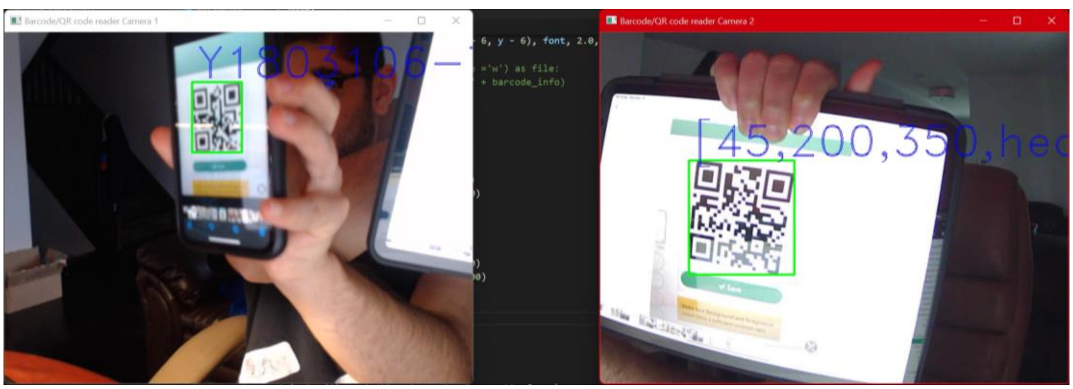

Figure 45 Camera based QR code scanner.

3.6.2 HMI using Node-Red

The Human Machine Interface (HMI) is the terminology used in the industry for inputting controls into an automation system. In the case of this apparatus, Node-Red was used to create a cloud-based UI that acts as the HMI. Node-Red provides a drag-and-drop-based user interface that allows creating UI and setting them up. The HMI Node-Red implementation is split into two parts:

- HMI Interface to Raspberry Pi communicates the request from the worker using the HMI to send commands to the Raspberry Pi to execute.
- HMI Data Processing and Display, which receives data from the Raspberry Pi in the apparatus and presents the data such that it is easy to understand,

The HMI for this application includes six main functions. Column 1 in Figure *46* provides touch-based buttons for the specified six functions. There are two buttons provided for each function to start and stop the functions, respectively.

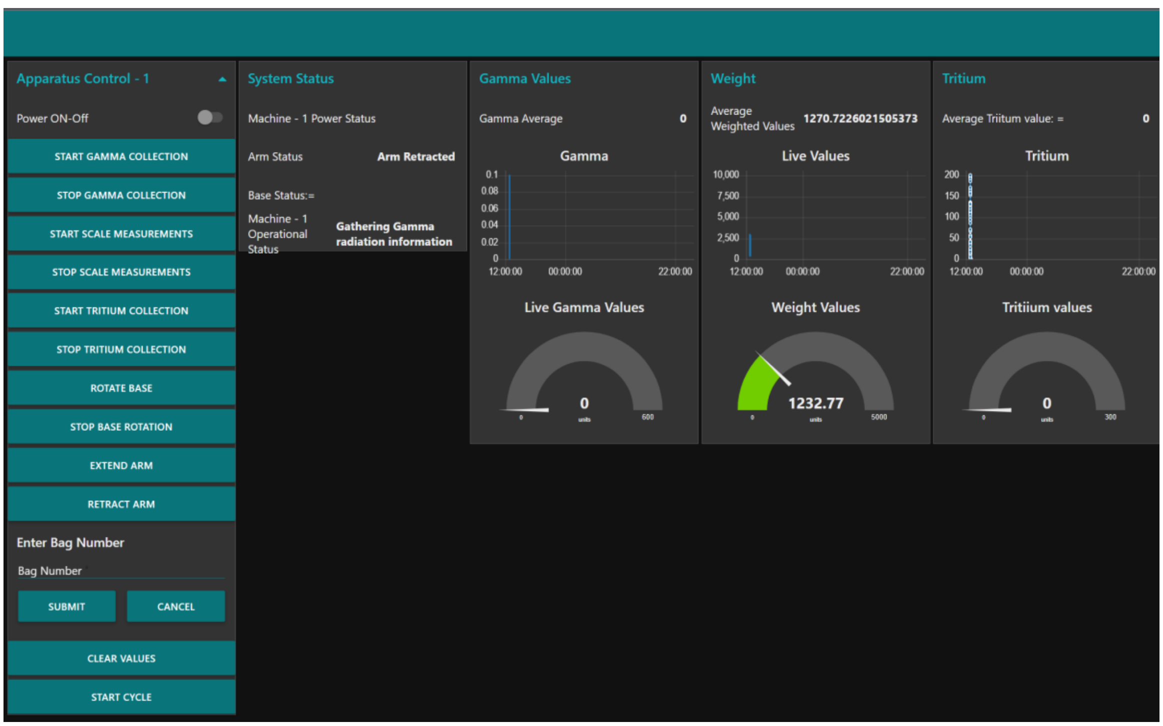

Figure 46 Node-RED based HMI

Function 1 - *Gamma Measurements:*

This function allows the user to start measuring the gamma radiation of the bag placed in the apparatus. While this function is running, a widget in Column 3 of Figure *46* shows the instantaneous and average values and plots the instantaneous values to capture the peaks. At the end of the measurement, the user can stop gamma collection, and on the screen the values for the average gamma values are shown.

Function 2 – *Weight Measurements:*

The weight measurement function allows users to start measuring the weight of the bag in the apparatus. The system accounts for rotation platform weight, ensuring only the weight of the bag will be shown. This function is to be used in conjunction with gamma measurement and the rotating base function. It allows all three times to be run simultaneously, saving time in the process.

Function 3 – *Tritium Measurements:*

This function allows the user to start measuring the tritium radiation of the bag placed in the apparatus. While this function is running, a widget in Column 5 of Figure *46* shows the instantaneous and average values and plots the instantaneous values to capture the peaks. At the end of the measurement, the user can stop tritium collection, and on the screen the values for the average tritium concentration values are shown.

Function 4 – *Base Rotating:*

This function allows the user to initiate base rotation to allow the bag in the apparatus to spin 360 degrees. This aids gamma radiation measurement in providing comprehensive data, ensuring no spots are missed.

Function 5 – *Linear Actuator activation:*

This function enables the user to penetrate the tritium detector probe into the waste bag so it can measure the tritium concentration in the bag.

Function 6 – Full Cycle:

This function effectively runs Function 1 to 5 in the correct order to complete a full measurement cycle that would occur of the bag in the receiving tent at LEP.

Programming the HMI in Node-Red is broken down into two main parts: HMI Interface to Raspberry Pi and HMI Data Processing. The next two sections dives into the details on the implementation of the two parts.

3.6.2.1 HMI Interface to Raspberry Pi:

Column 1 Column 2 Column 3 Column 4 Column 5 Column 6

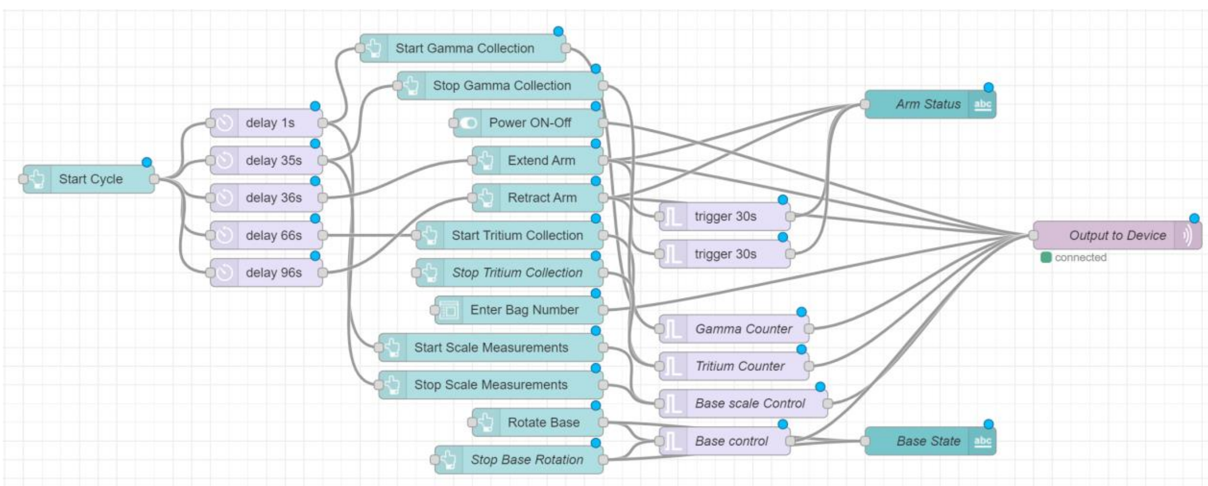

Figure 47 HMI / UI Interface Node-Red Code

This part is where the input is taken from the worker to control the automation. Commands are sent from Node-Red to the Raspberry Pi. In Figure *47*, the HMI interface to the Raspberry Pi is shown segregated into six different columns. Each of the columns represents a different stage in the interface flow. This can further be broken into two sections: the turquoise elements represent visual changes to the Node-Red HMI, and the purple elements represent backend tasks because of HMI interaction by the user. Each of the elements has detailed configurations for appearance and placement in UI; this applies primarily to turquois elements. Here is a description of each of the columns and their respective functions.

- Column 1: Contains the "Start Cycle" toggle, which is a user interface button that is pressed to initiate starting the cycle. This button is shown on the HMI/UI, which is touch enabled. This toggles the rest of the functions in an order that are delayed artificially by delays.
- Column 2: Contains delays that are added to ensure that when a full cycle is initiated, the order of tasks completed is maintained. For example, from Figure *47*, after 1 second, "Start Gamma Collection" and "Start Scale Measurement" are initiated, ensuring if two tasks can be parallelized. This can also prevent tasks that are not meant to run simultaneously, such as tritium measurement and weight measurement.
- Column 3: Contains the HMI toggles for invoking individual functions manually.
- Column 4: This column contains pulses that send the command from the previous column 3 to column 5. For instance, the gamma detector that is being used on the AR600 can only transmit data over the serial connector to the Raspberry Pi at a polling rate of 1 Hz, meaning it can only send one value per second. This column ensures that that time is matched, so the Raspberry Pi is told to only look for a value from the HMI at 1 Hz. Similarly, the "scale measurement" is told to ask for a value every 200 ms, as the scale being used is much faster than the gamma detector. This column is configurable based on the items

that are being used in automation. For example, if the gamma measurement detector is upgraded and can support a faster polling rate, its respective pulse toggle can be sped up to accommodate.

- Column 5: This column contains elements that are used to display the status of what the system is doing to the HMI/UX as a reference for the operator to determine how far it is in the cycle or to aid in diagnostics. If the status of the system does not correspond with the action of the system, then there is an issue.
- Column 6: All elements are tied to this single operator, which is responsible for sending the instructions to the Raspberry Pi through MQTT.

3.6.2.2 HMI Data Processing

Column 1	Column 2	Column 3	Column 4

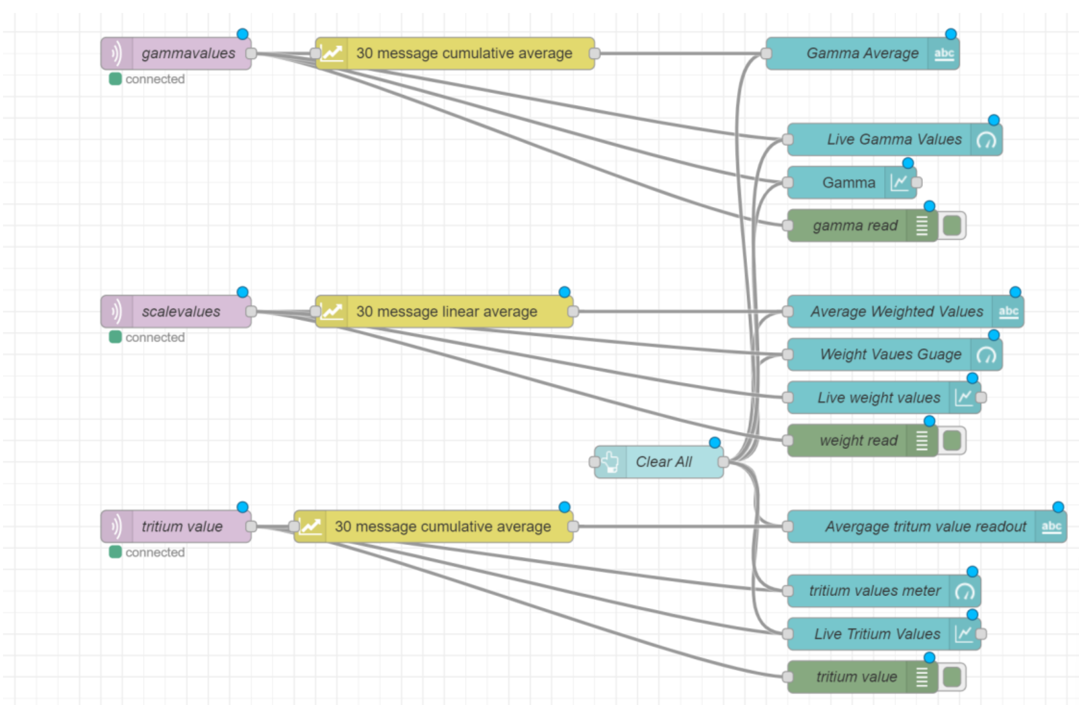

Figure 48 Communication with Raspberry Pi

In Figure *48*, the data processing and visualization of the HMI aspect of the Node-Red is shown. The section is segregated into four different columns. It is further divided into 5 sections determined by the colour of the element.

- The turquoise elements represent visual changes to the Node-Red HMI.
- The purple elements represent data being received from the Raspberry Pi via MQTT, with an indicator showing connection status.
- The yellow represents the data processing that occurs in Node-Red to the incoming data from the Raspberry Pi.
- The light turquoise represents HMI input to clear saved values in the HMI elements.
- Lastly, the green elements indicate payload, which refers to the actual data that is being transmitted in a message.

- Column 1: Three values are coming from the Raspberry Pi using MQTT. Each value has its own unique ID known as a "topic." Each toggle in column 1 is looking for a specific topic that, when it arrives, will update the HMI/UI. These topics are what allow multiple different apparatuses to be merged into one UI but shown separately for the user. This is part of the modularity aspect, as more elements can be added to accommodate for added detectors, and sensors.
- Column 2: This toggle takes the raw values from the Raspberry Pi and calculates a rolling average of them, which is beneficial for certain fast polling items such as the scale. More specific calculations can also be defined, such as weighted averages, for further data analysis and filtering.

- Column 3: Is an HMI/UI input that clears all the values on screen after the values are recorded after each run. This is placed there so the averaging functionality does not use values from the previous test, creating false averages. It also provides a clean starting point for manual observation on the charts from Figure *46*.
- Column 4: The turquoise toggles are updating the HMI/UI values, and the green toggles are payload toggles that are required in Node-Red to receive values

3.7 Challenges and Constraints

The design can be concluded based on how it satisfies the technical requirements set in Section 3.3. The design satisfies the gamma and tritium measurements with the incorporation of the AR600 and Tyne 7063 detectors. They can send measurement values to the Raspberry Pi using serial communication and to the worker remotely using MQTT and Node-Red.

Secondly the rotating scale satisfies the weight measurement criteria allowing for the weight to be measured while gamma measurements are taken. QR Code based bin identification while not implemented into Node-Red can be done using two methods: using a scanner or camera based. MQTT enables remote operation of the apparatus as long as both the apparatus and the computer used to access MQTT are both connected to the internet.

Lastly, the use of MQTT and Raspberry Pi ensures that multiple apparatuses can simultaneously be used in the future for improved scalability. The Node-Red based HMIs can be expanded to accommodate multiple UIs that show different dashboards for controls and process progress as shown in Figure *49* and Figure 50. The Raspberry Pi's USB ports can be extended using USB hubs to add additional detectors. The programming languages used are directly transferrable to different platforms allowing for easy transition between different microcontrollers. This concludes that the design implementation obtained all the six technical requirements set.

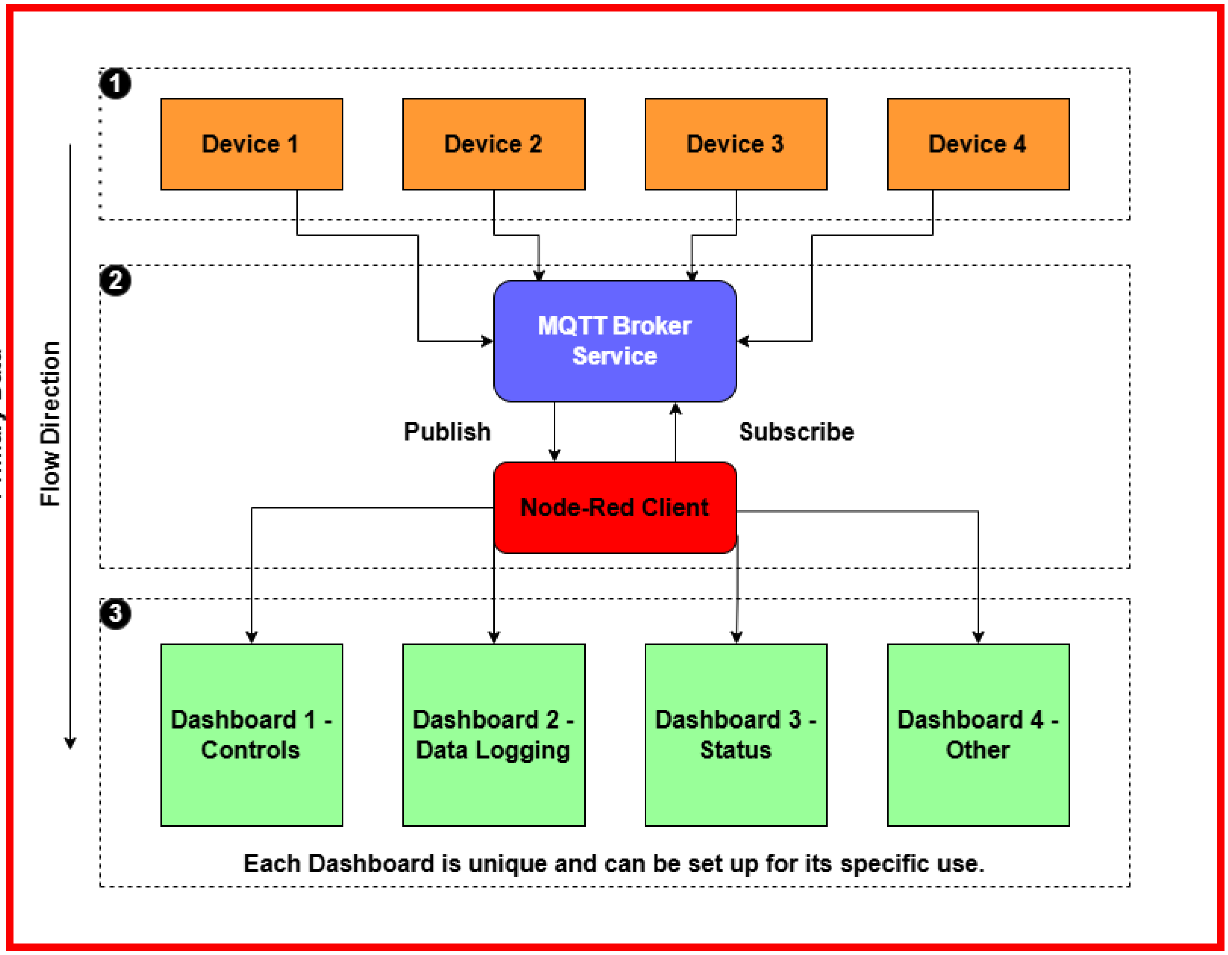

Figure 49 Multiple Apparatus Design

There are several constraints that influenced certain design choices. There are three main constraints in the design process. Firstly, limited detector availability, detectors are the most expensive part of the design, and as a result it hindered some of the performance of the apparatus which we will see in the results sections. The detectors effect the performance of the design but does not affect the functionality of the apparatus.

Secondly, Cost-effective design: The apparatus was built to demonstrate a proof of concept at a low cost, which limited the sophistication of some components such as the linear actuator, the one used in the device is slow at 30 seconds to extend.

Lastly, Remote testing: Due to the location of the build, the apparatus could not be tested within LEPs facility specifically the BMR as it is considered hazardous. As a result, the design and building of the device was carried out at McMaster in the Engineering Tech Building.

Chapter 4.0 Results

Automation for LLW has been set up that allows multiple different apparatuses to potentially work together in the future. This is not tested as there was only one apparatus at the time; this information can be inferred as node-red allows to create multiple controls for different devices as seen in Section 3.6.2. One HMI output from the user can be written to multiple different apparatuses simultaneously. Figure *50* shown below shows 5 devices that are placed in the receiving tent. A worker can load all 5 machines simultaneously and then run the automation, allowing 5 bags to be processed simultaneously.

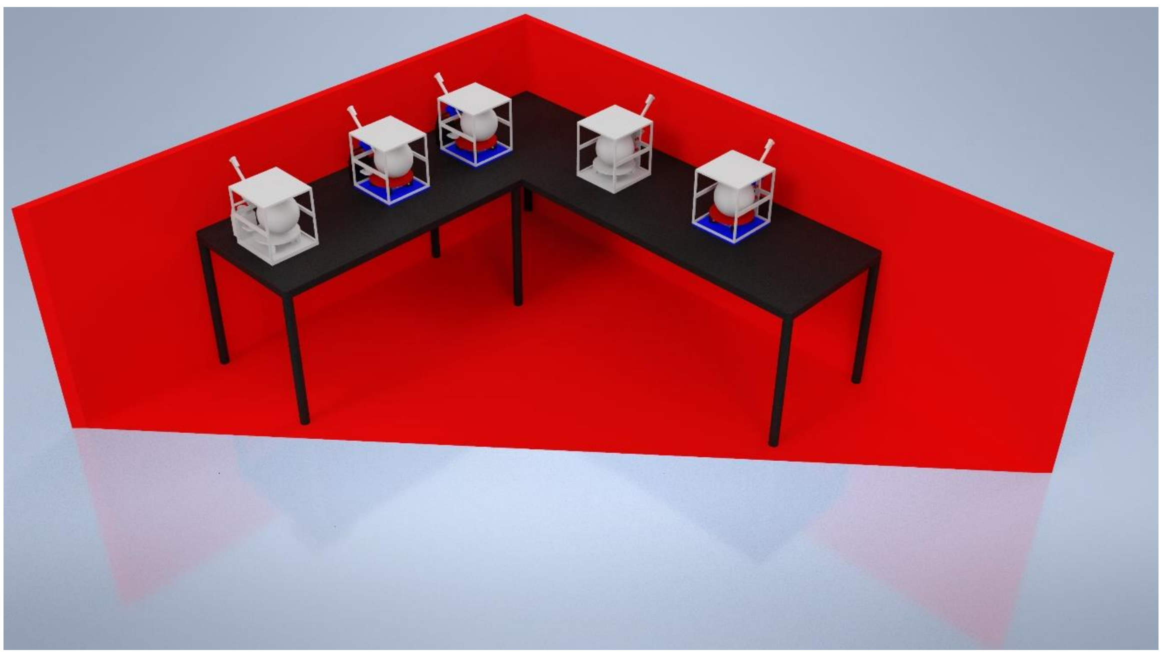

Figure 50 Simulation demonstrating multiple Apparatuses in Receiving Tent

4.1 Process Improvements Projections:

There are significant changes to process when we compare the manual process to the automation aided process. Prior to automation, the process involved four distinct steps, each requiring a worker, including tasks such as gamma and tritium testing of waste bins. Figure 36 indicates the

4 steps in the Low-Level Waste Automation Apparatus section. The manual process involved four workers physically handling each bag, requiring approximately 120 seconds per bag roughly 30 seconds per step, and process has to be done sequentially. The manual procedure not only takes more time, but it also raises the possibility of human error and potentially radiation exposure. The cramped area in the reception tent increases the risk of contaminant spread if an event occurred. However, with the introduction of automation, the process becomes significantly more efficient, as a single worker, with the assistance of an automated apparatus, can now perform the tasks of four workers and process up to five bags at once in a best-case scenario, as illustrated in Figure *50*, dramatically increasing throughput. Utilizing automation optimized gamma and tritium detectors, processing time per bag may be reduced from 120 seconds to roughly 30 seconds. as seen in Table 5.

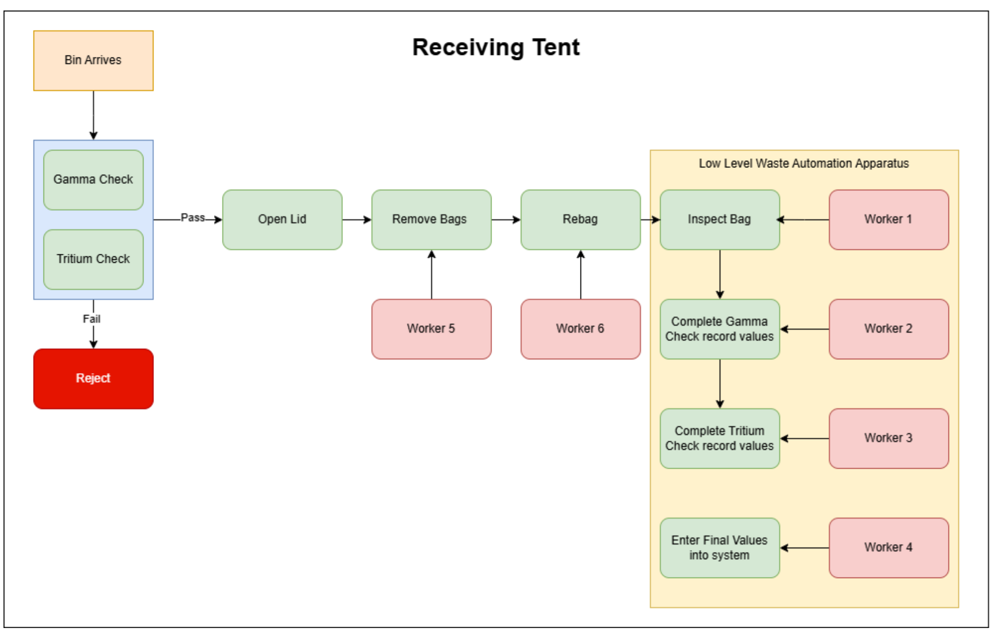

Figure 51 Process prior to Automation in Receiving Tent

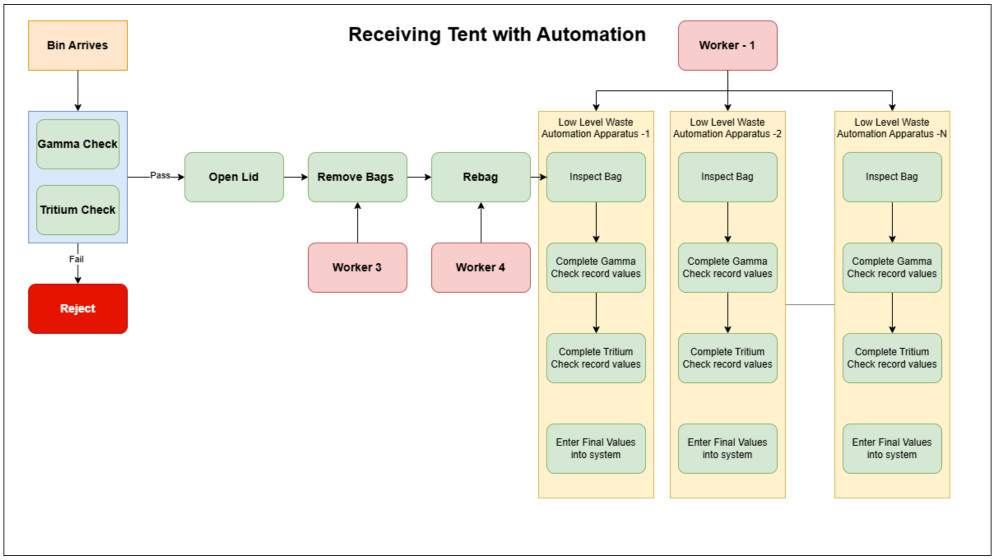

Figure 52 Proposed Process with Automation in Receiving Tent

4.2 Productivity Improvements

Introducing automation significantly enhances productivity as seen in Table 5 which shows projections of productivity increases. The automation allows for a single worker to complete the work of 4 people improving efficiency and reducing the total labour requirements. Additionally, when the automation system is expanded from one unit to 5 units it allows for a single worker to process 5 bags simultaneously.

When we improve the system with faster detectors and linear actuators, the total time per bag can be reduced from 120s to 30 seconds. This provides a substantial productivity improvement allowing for more waste to be sorted. This is a 75%-time savings for a single unit, and up to 95% for a 5-unit setup. Table *6* and Figure *53* Bag Processing Time Savings from Table 6 shows the productivity increases when we estimate the time savings.

Table *6* shows an ideal automation apparatus where the time taken to complete a single bag is 30 seconds. The breakdown is as follows if the gamma detectors can provide readings in 10 seconds allowing gamma measurements and weight measurements to be completed in 10 seconds (Rotation speed of $\frac{360}{10} \rightarrow \frac{36°}{\text{second}}$). A linear actuator that can quickly pierce the probe into the bag (1-2seconds), complete the tritium concentration check in 10 seconds, and retract the actuator in (1-2seconds). Allowing for a total time of 30seconds per bag.

Table 6 Timing Approximation of Bag Checking

Bag Count	Current LEP time [s]	Time with Automation [s]	Time with Scaled Automation [5 Units] [s]	% Saving Automation	% Savings Scaled Automation [5 units]
2	240	60	30	75	87.5
4	480	120	30	75	93.75
8	960	240	48	75	95
16	1920	480	96	75	95
32	3840	960	192	75	95
64	7680	1920	384	75	95
128	15360	3840	768	75	95
256	30720	7680	1536	75	95

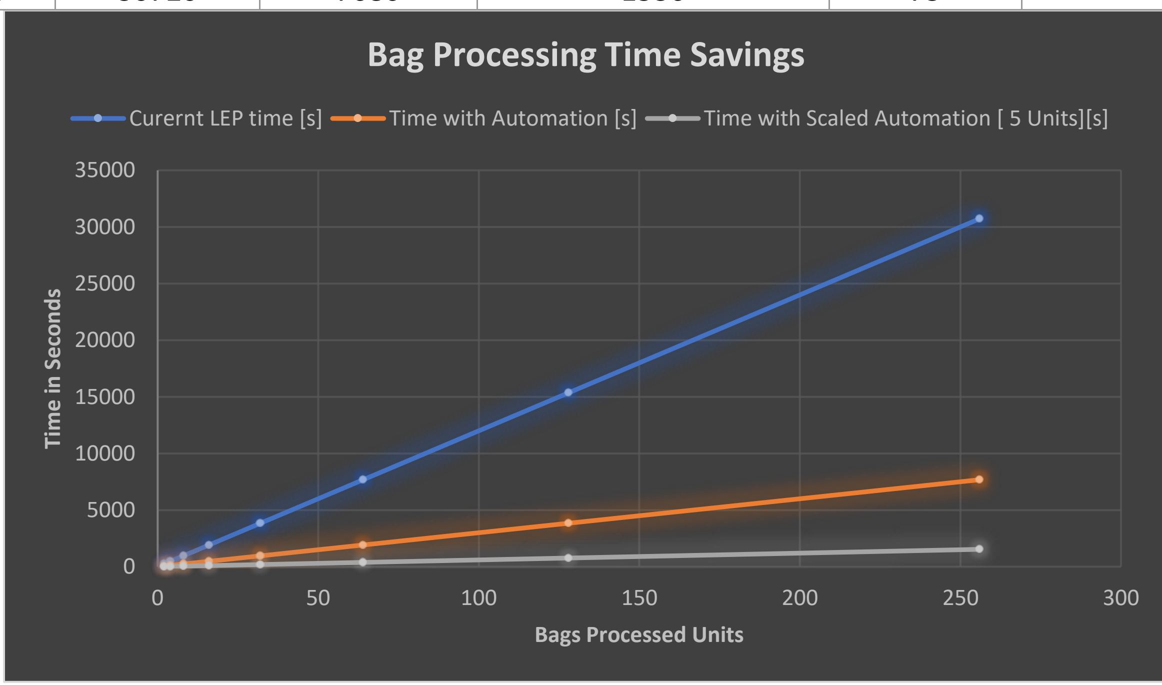

Figure 53 Bag Processing Time Savings from Table 6

Detailed Breakdown of Table *6* Timing Approximation of Bag Checking.

- The bag count is the number of bags that are being processed in total, now this can be from one bin or an accumulation of all the bins measured over a given period.
- Current LEP time represent the rough time it takes for LEP to complete measurements of the bags depending on the amount. It roughly takes 120 seconds per bag for LEP to process based on their current process.
- Time with automation represent the time taken to measure x amounts of bags with each bag taking 30 seconds to complete assuming ideal detectors and linear actuators are used.
- Time with automation [5 units] represent the time taken to measure x amounts of bags using 5 apparatuses to speed up the time required. The benefit from this scenario only occurs when 5 or more bags are being measured simultaneously as indicated by Table *6*.
- The last two columns shows the time savings that are achieved from LEPs manual process compared to a one-unit apparatus setup and five unit apparatus setup.

Figure *53* shows a visualized graph that shows the time savings per bag based on manual process vs automation is used.

4.3 Standardized Measurements in Gamma Detection for LEP Applications:

While accuracy is not the utmost important during the receiving tent, it is still to be considered as workers in the next stage of sorting will come near the waste bag checked during this step. Currently manual measurements of gamma emissions are taken by workers. As mentioned earlier this can introduce variability as differences between worker A and worker B handles the detector for measurements leading to slightly different values. Automation provides a potential solution by standardizing the measurement process and minimizing human error to improve consistency and reliability of gamma measurements.

When a worker is measuring the bag manually, the pattern they chose to scan with the detector, and the placement of the detector relative to the bag can create a run-to-run variance as minimal changes can create changes to the final measurement as ultimately the worker is reading the value on the detector and reporting it. With the aid of automation this variability can be reduced if not eliminated. The apparatus designed can control the rotational speed, and the detector is fixed in spot. This ensures that for every rotation the waste bag is measured identically for every bag that is placed into the apparatus. Due to logistic reasons preventing the apparatus from being tested in the receiving tent, the theory projects that automation will allow for standardized measurements which in return improves accuracy.

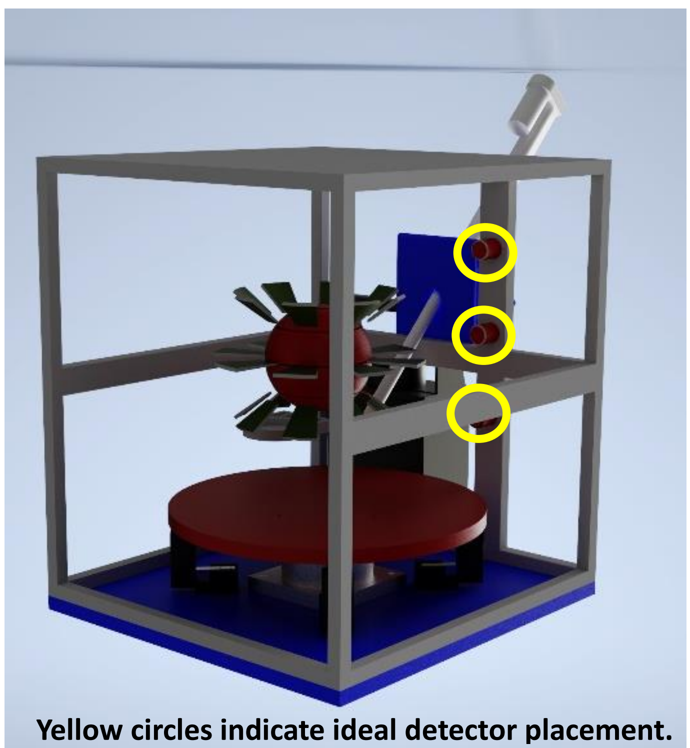

Figure 54 Apparatus showing emission directions from waste bag

In Figure 39, the emission pattern from a waste bag is depicted, and it is showing the ideal placement and number of detectors in red. The detectors remain fixed at all points while the base is allowed to rotate at a constant rate. This ensures that the same number of measurements are collected during every rotation.

Table 7 Showing relationship between rotation speed, number of detectors and gamma measurements collected

Rotational speed [degrees/second]	Detectors	Points per rotation
5	1	72
10	1	36
12	**1**	**30**
20	1	18
30	1	12
40	1	9
50	1	7.2
5	2	144
10	2	72
12	**2**	**60**
20	2	36
30	2	24
40	2	18
50	2	14.4
5	3	216
10	3	108
12	**3**	**90**
20	3	54
30	3	36
40	3	27
50	3	21.6

A key factor in the accuracy of gamma measurements is the amount of measurements points that are collected per rotation. In Table 6 the relationship between rotation speed, the number of detectors and the total amount of measurement points can be observed. In the table 12°/s has been highlighted which represent the current configuration of the apparatus. It allows for 30 measurements to be taken assuming the detector measures at 1Hz which is the case.

Adding more detectors the number of measurements obtained increases proportionally allowing for a comprehensive coverage.

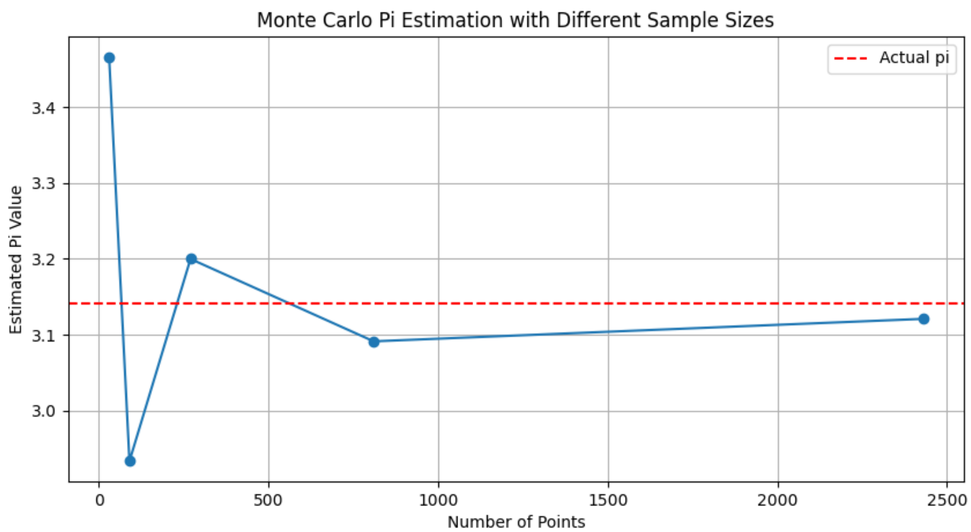

Figure 55 Monte Carlo Pi Estimation

Additionally, we can refer to the Monte Carlo method which is used to approximate the values of pi. The accuracy of the output value increases as more random points are used. The same logic can be applying to gamma measurements. Improving accuracy can be obtained by obtained larger amount of measurement, adding additional detectors, or faster detectors. Figure 40 demonstrates that increasing the number of points in Monte Carlo method improves accuracy. Four points were tested; 30, 90, 270, 810, 2430.

The implementation of automation to LEPs process provides multiple advantages in standardization measurements. It helps eliminate human errors and provides consistent measurements which leads to a more reliable and accurate measurements. Adding automation will also significantly help improve the efficiency and safety of the workers at LEP.

4.4 Effectiveness of HMI

A robust Human Machine Interface (HMI) provides several improvements in addition to the process, productivity and standardized measurements. HMI allows for re-checks of gamma, tritium, and weight measurement while ensuring consistency without changes in technique if a test fails. Simplifies the useability of the apparatus. The apparatus built utilized a touchscreen interface for controlling the HMI, or a separate computer internet connection, eliminating the need for range tests. Node-RED enables adjusting the polling rates of the data input from MQTT speeding up the readings or slowing them down, currently they are slowed down to match the polling rates of the detectors. The polling rates are asynchronously allowing for gamma detector to be slower than the weight measurements even through they operate at the same time. Additionally, Node-RED supports multiple dashboards, enabling independent control of different apparatuses or screen, offering flexibility between status and data centric views and controls. Figure [add in Node-Red figure] demonstrates the current state of node-RED dashboard, it is not limited to this and can be expanded further. Including sections enabling different apparatus to be controlled, and other UI and HMI based toggled to be added. MQTT is not explicitly linked to Node-RED and can be integrated with other platforms such as Azure IOT and Windows .NET allowing for a wide range of devices to be used to control the automation. A notable advantage of the HMI is the ability to manage the apparatus while obtaining live measurement readouts using a predefined averaging procedure, which eliminates the current manual documenting process at LEP. Node-RED is implemented with basic data processing but provides groundwork for future expansions to detailed data processing. Furthermore, the technology lays the groundwork for a direct database connection, enabling bag numbers and associated measurements to be automatically recorded into LEP's database, removing the need for human data entry further removing human errors.

4.5 Summary of Results

LLW Sorting Apparatus shows projections indicating increased efficiency, productivity, and measurement accuracy in low-level waste processing. By minimizing human interaction and allowing a single worker to handle a single or multiple machines, processing time per bag has been reduced from 120 to 30 seconds. Automation enables standardized gamma and tritium measurements, reducing human error and accurate results. Implementing a Node-RED based HMI enables apparatus control, real-time readouts, and basic data processing, with potential future extension for options such as direct database connections. These enhancements provided by automation have simplified operations, improved safety at LEP.

Chapter 5.0 Conclusion and Discussions:

5.1 Summary of Key Findings.

This research focuses on the implementation of Low-Level-Waste Measurement Automation Apparatus to demonstrate it can provide significant improvement to LEPs existing process, productivity, and providing a path for standardized radiation measurements. The apparatus allows for reducing the number of workers involved during the process that takes place in the receiving tent. It enables a single worker to handle multiple tasks simultaneously potentially reducing the process time from 120 seconds to 30 seconds, providing a time reduction of 95% when multi-apparatus setup is considered. Additionally, the incorporation of Industry 4.0 techniques has enhanced the accuracy and consistency of gamma and tritium radiation measurement and ultimately minimized the potential human error to provide reliable results. The improvements and abilities the apparatus unlocked with the aid of automation not only streamlines the operations but helps reduce additional potential radiation exposure to workers as less workers are being exposed.

Node-RED allows for a simple HMI to be added as a means of controlling the Apparatus simplifying the control of a single or multi-apparatus configuration. It provides real-time data visualization and data processing capabilities and can be further expanded to a database. Unfortunately, the current apparatus has not been fully tested with multiple systems, as there was only one system. However, node-RED has the potential to scale the automation with multiple apparatuses as seen with the projected time savings. Future work is discussed in the next section discussing improvements that can be made to the existing apparatus as well as how it can be expanded to other sections of LEPs processes.

5.2 Contributions to the Field of Nuclear Waste Management Processing

There is a significant backlog of waste that needs to be sorted, as indicated in Section 2.2. This thesis demonstrates how automation can significantly speed up the processing of waste. Furthermore, if LEPs and in return Canada develops a method of effectively and efficiently sorting waste. The possibility of importing waste from other countries to sort it for them becomes viable for a profit for Canada and in return LEP. This would also aid the reputation of nuclear engineering and the associated perspective that the public has of nuclear waste (*Q&A*, 2020) .If shown to the public that waste is processable and not all waste is to end up in landfills they may be a change of perspective allowing for nuclear energy to become a more popular method. Additionally, successful LLW sorting can open paths to sorting higher categories radiation waste more effectively.

5.3 Future work

5.3.1 Detectors

To improve the apparatus and the automation the biggest changes need to come with the detectors that are being used. The detectors that were used in the apparatus are extremely slow, polling 1 reading per sample. It is to be noted that the detector does internal hardware-based averaging and noise reduction. Referring to Section 2.7.3 we can see that multiple detectors appear in a cylindrical form factor, this is an ideal shape for the detector, compared to the AR600 that is used in the apparatus as it is meant to be an area monitor. There are methods to make detectors more IoT friendly relying on a wireless method or improving the connectivity of the wired interface to offer quick implementation into automation devices. POE or Power over Ethernet is a standard that is used readily in the automation domain providing both power and data over a single cable. Additionally, we see that all the detectors have different methods of communication, requiring custom software or cables to communicate with the detectors. A Standardized method of communication between different detectors can also help streamline implementation.

5.3.2 Automation Controller

For the demo apparatus a Raspberry Pi was used, while it provided the required computational power and software environment to complete the project, in the future a more cable controller would be better fit, either a PLC with Wi-Fi and MQTT or a custom FGPA based solution that is specific to LEP integrating data from a custom detector and allowing for hardware-based data processing. Raspberry Pi is a 5V/3.3V device and does not contain support for automation equipment with traditionally relies on 24V. This complicates things as customs for everything must be made to step voltage down. It is especially an issue when you wish to communicate via analog methods, as the RPI does not support voltage-based control as there is no DAC. It is also not a computational powerhouse, especially when AI based tasks are added. There is better microcontroller injunction with PLC devices that can enable advanced automation. Design of a PLC-Integrated Object Detection for Categorizing Conveyor talks about integrating object detection into a PLC base automation system with the aid of a NVIDIA Jetson (Rothong et al., 2023).

5.3.3 Improvements to HMI

Node-RED is currently used to create an HMI that provides a basic interface for controlling the apparatus and viewing the live readout of the data. Figure *46* shows a basic interface that relies on MQTT. As more detail and specific processes get added, a more granular HMI will be needed, and this requires switching over from node-RED. Future improvements to node-RED and further improve the effectiveness of the apparatus.

5.3.4 Convert Additional Processes

Figure *4* shows the detailed breakdown of LEPs process for LLW sorting. This paper talks about automation in receiving then, and even within the receiving tent only and the benefits that automation brings. There are other opportunities within LEPs process to add automation too. Initial measurements when the bin arrives at the facility and receiving tent are future areas that can benefit from automation, bringing it together with the one discussed in this paper to create a comprehensive system further reducing worker interactions and ensuring standardized measurements are also brought to other parts of the process.

In conclusion, while the current apparatus makes significant progress in automating the LLW measurement process, future improvements to detectors, automation controllers, the HMI, and other processes will improve the system's efficiency, scalability. These ongoing advances will minimize human involvement, expedite waste management, and assure consistent, precise measurements, all of which will contribute to the long-term aim of enhancing nuclear waste handling safety and productivity.

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