DESIGN AND FABRICATION OF A REVERSE VENDING MACHINE

A Final Year Project Report

Presented to

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

Department of Mechanical Engineering

NUST

ISLAMABAD, PAKISTAN

In Partial Fulfillment
of the Requirements for the Degree of
Bachelors of Mechanical Engineering

by

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June 2023

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Titled: "DESIGN AND FABRICATION OF A REVERSE VENDING MACHINE" be accepted in partial fulfillment of the requirements for the award of MECHANICAL ENGINEERING degree with grade ___

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ABSTRACT

Plastic pollution is one of the biggest challenges of the 21st century. Polyethylene Terephthalate (PET) is 100% most recyclable plastic In Pakistan, 1 million tons of PET waste is produced every year, however, there is no formal mechanism of PET waste collection, disposal and recycling.

Learning from global experiences, we aimed to design an indigenous Reverse Vending Machine (RVM) that is user-friendly, cost-effective and caters to local needs. We designed and fabricated an RVM with both single and bulk intake able of accept PET bottles and reject non-PET bottles with high accuracy. For this purpose, we used NIR spectroscopy, ultrasonic sensors and loadcell for identification of PET bottles. A conveyor and flap mechanism were used for conveying and diverting the bottles to the rejection chute and collection bucket.

ACKNOWLEDGMENTS

All praise belongs to Almighty Allah for blessing us and providing us the strength to complete the final year project successfully.

We would like to thank our parents for the constant emotional support that helped us stay motivated and without which this project would not have been possible.

We would like to express our deepest gratitude to our supervisor Dr. Jawad Aslam, who was a source of constant inspiration for us, guiding us throughout the project and tendering important advice. We would like to thank the staff at the Tribology and CIM lab and the instructors at the MRC for helping us during the manufacturing of the machine. We would especially like to acknowledge the role of Mr. Faisal in facilitating the manufacturing process and guiding us in the process.

We are most thankful to our fellow undergraduate colleagues for their eager suggestions and feedback. Finally, our sincere gratitude to all those who have supported us in completing the project directly or indirectly.

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ABBREVIATIONS

RVM	Reverse Vending Machine
PET	Polyethylene Terephthalate
XRF	X-Ray Fluorescence
PVC	Poly Vinyl Chloride
HDPE	High Density Polyethlyne
PS	Polystyrene
NIR	Near Infrared
SPDT	Single Pole Double Throw switch
DPDT	Double Pole Double Throw Switch

CHAPTER 1: INTRODUCTION

1.1 Motivation

Plastics have become an integral part of our everyday life with uses in apparels, construction, packaging, transportation, machinery, appliances etc. Its popularity is due to its unparalleled properties and cheap and easy availability. To cater for such a huge demand, the production of plastic is increasing exponentially since the 1950s from 2 million tons to approximately 460 million tons produced in 2019 reflecting a 230-times increase [1] (Figure 1). It is also estimated that this production is going to double in the next twenty years.

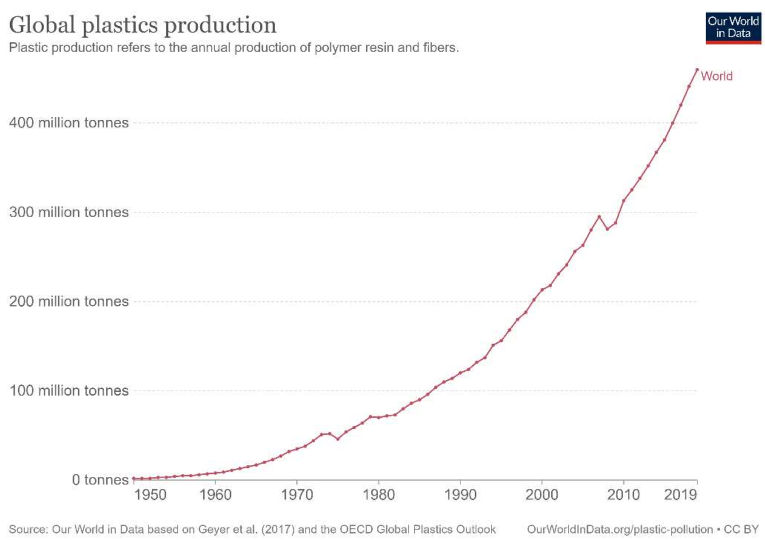


Figure 1: Increase in global plastic production during 1950 - 2019

The use and disposal of plastic is, however, a source of paramount concern for the future of the planet due to its numerous adverse effects. The buildup of plastic can pollute water bodies which is a major health concern as it can cause multiple diseases such as obesity, diabetes, cancer etc. Similarly, the leakage of plastic into oceans is injurious to marine life. Moreover, plastic takes hundreds of years to degrade and keeps piling up in water bodies. According to an estimate, 12.7 million metric tons (MTs) of plastics are released into the oceans every year. [2] Likewise, the plastic sector will be responsible for more than 15% of the global carbon budget by 2050. [3] Thus, the use of single-use plastic products (SUPs) needs to be discouraged and steps must be taken to recycle and reuse plastic to reduce the strain on the environment.

Polyethylene Terephthalate commonly known as PET is a 100% recyclable plastic with a resin identification code of 1. [4] (Figure 2) It is commonly used as a packaging material for food and beverages, mostly used as bottles. Its high recyclability makes it a better option for the environmental if augmented with efficient recycling and reusing measures. Globally, innovative methods are being employed for collection, management, and recycling of PET waste. One such method is the use of Reverse Vending Machine (RVM). RVM is a machine designed to accept plastic bottles in exchange for a monetary incentive in the form of a receipt/voucher or e-wallet money. This has been an effective concept whereby multiple countries have increased their recycling rate.

Figure 2: Symbol of PET with its resin identification code of 1

1.2. Problem Statement

Pakistan is the 2nd largest user of PET bottles in South Asia with 0.4kg PET waste produced per capita per month. Thus, Pakistan produces 1 million tons of PET waste per year which is a great strain on our waste collection system and the environment. Despite its large quantity and easy recyclability, no formal mechanism exists for the disposal of PET waste and child labor is usually employed for the collection of PET waste. [5]

While there are more than 100,000 RVMs have been installed worldwide, in Pakistan the concept has not been able to catch on except for some pilot projects. The main reason for this is that imported machines are extremely expensive and without the government's support does not make for a viable business. Similarly, these imported machines are not tailored for the local market that is prone to cases of fraud and misuse.

The development of an indigenous Reverse Vending Machine will not only contribute in solving the problem of plastic but also boost the recycling industry by the provision of high quality, clean PET waste that can be used for high end recycling applications. Beverage industry has already shown interest in moving towards the use of recycled PET for their bottles.

The aim of this project is to "*Indigenously design and develop a cost-effective reverse vending machine that is able to effectively handle PET bottle waste and reject non-PET material with high accuracy.*"

For catering to the local market, the machine not only needs to be ergonomic in design enabling maximum number of people to use the machine. The inclusion of bulk intake into the machine will make such a machine highly popular. Moreover, the machine needs to be robust in its working and be able to reject non-PET bottles with high accuracy.

1.3. Objectives

The Objectives of the project include:

1. Design of the machine casing and mechanisms
2. Design of the control system and algorithms

3. Simulation and motion study
4. Fabrication and iteration of the prototype

CHAPTER 2: LITERATURE REVIEW

An extensive literature review was conducted keeping in view all stages of the design and manufacturing and the various aspects of the machine. The focus during the review was on the features that make the machine more accessible, the prevalent and new design techniques, available option for control systems etc.

2.1. Existing PET recycling supply chain

In the absence of a formal collection and disposal system for plastic bottles, an informal supply chain exists in Pakistan in which the PET bottles mixed with other household and industry waste is picked by scavengers and waste pickers (usually child laborers) who then sell this to junk dealers who eventually sell it to informal recyclers. [5] This PET is highly unclean and of low quality due to its mixing with other waste and thus can only be used for low level products. There is high demand of clean PET for higher end applications such as reuse of the bottles by beverage companies. The proposed RVM thus needs to be able to provide good quality clean PET bottles to the industry. It should also be able to capture unrecycled PET bottles by adding an incentive to the bottle consumer to return the bottle to the RVM. [6]

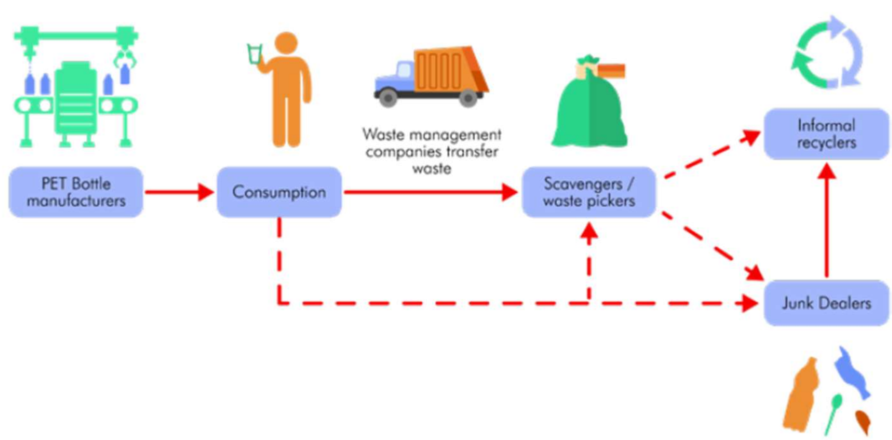


Figure 3: Supply Chain for PET Recycling

2.2. Existing Detection Mechanisms

2.2.1. Capacitive Sensors:

Capacitive Sensors are a type of proximity sensor which can detect solids and liquids without physical contact. To detect materials, capacitive sensors emit an electric field and

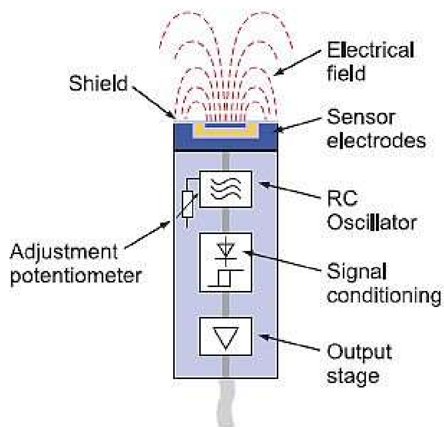


Figure 4: Capacitive Sensor

measure the change in the electric field caused by the nearby material. The difference in the capacitance of materials can be used to differentiate between them. Capacitive sensors work best at a close range. [7] Capacitive Sensors are typically used for separation of metallic and non-metallic materials with high accuracy such as the separation of iron, steel, aluminum etc. However, they can also be used for other materials such as wood, paper or plastic. [8]

2.2.2. Photoelectric Sensors:

These sensors work by emitting a specific wavelength of light and measuring the received light. The difference between the intensity of the transmitted and received light can be used to differentiate the material based on its transparency and reflectivity. [9] Based on their mode of operation they are further classified as:

i) Diffuse-reflective Sensors:

The emitter and receiver are installed in the same housing. In the absence of any material in front of the sensor, no light strikes the receiver. In the presence

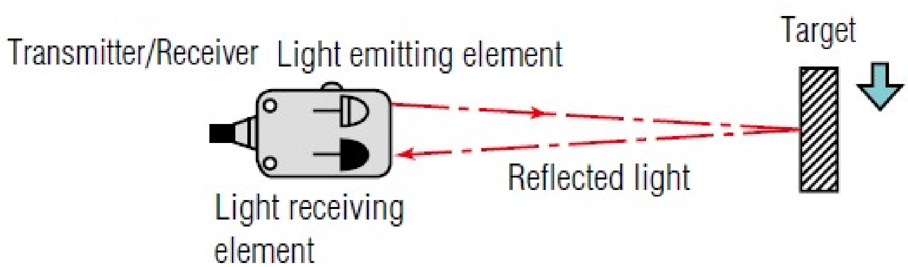


Figure 5: Diffuse-Reflective Photoelectric Sensor

of an object, the light reflected from the object enters the receiver and the change in light intensity is used to detect the presence of the object.

ii) Retro-reflective Sensors:

Similar to diffuse-reflective sensor, the emitter and receiver are installed in the same housing. However, due to a use of a reflector, in the absence of any material, maximum light intensity is captured at the receiver. In the presence of a material, the intensity of the reflected light becomes lower, and the decrease is thus used to detect the presence of the material.

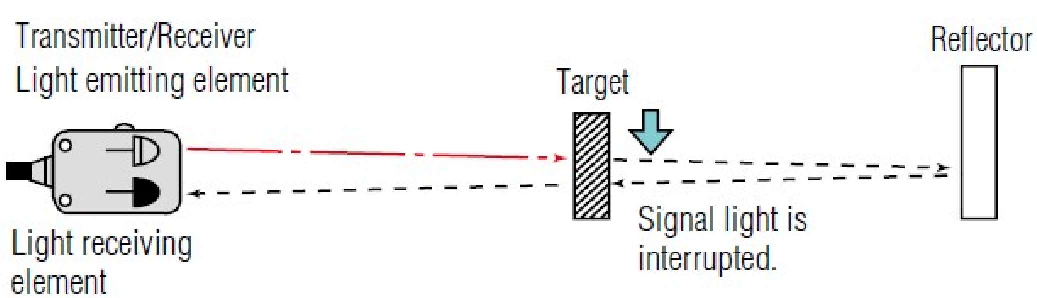


Figure 6: Retro-reflective Sensor

iii) Through-beam Sensors:

The emitter and receiver are in two different housings. When the object cuts the axis joining the emitter and receiver, the intensity if light reaching the receiver decreases which is maximum when no object is between the emitter and receiver. Through-beam sensor measures the amount of light transmitted by the object instead of reflected light. [10]

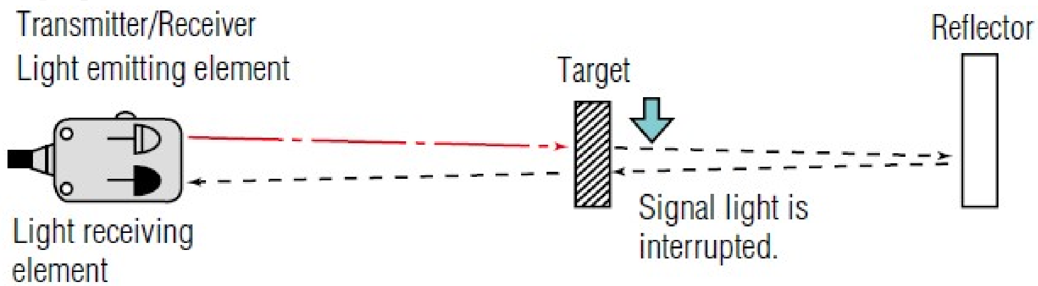


Figure 7: Through-beam sensor

2.2.3. X-Ray Fluorescence:

XRF works by irradiating the sample with X-rays of sufficient energy to dislodge an electron from an inner shell of an atom. To regain stability, electron from a higher shell fills the vacancy left by the leaving electron, thereby releasing energy which corresponds to the X-Ray region. This energy is measured and varies depending on the atoms present in the material. [11] [12]

To efficiently differentiate between the PET and Poly Vinyl Chloride (PVC), X-Ray Fluorescence (XRF) is a reliable method which makes use of the difference in molecular structure. The PVC contains a chlorine atom which behave differently to the X-Rays and develop a unique pattern which can be easily used for its classification from PET bottles. [13]

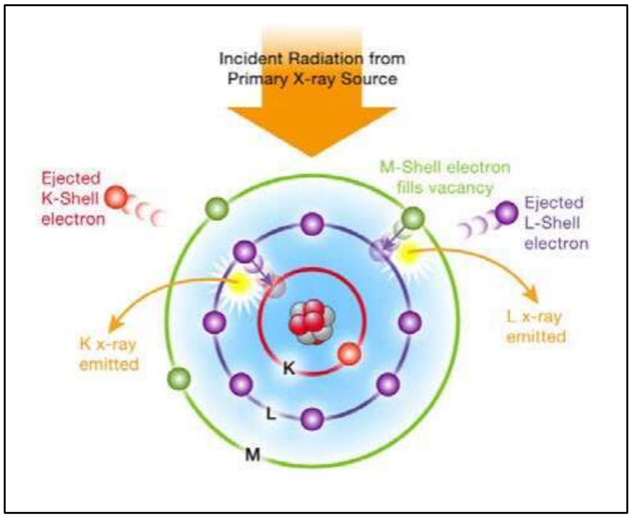


Figure 8: Working of XRF

2.2.4. Load Cell:

PET is a lightweight plastic. This property can be used to differentiate PET from other kinds of plastic and other heavy materials by measuring its weight using a load-cell. However, only using a load-cell can lead to unnecessarily higher rejection rates and low accuracy in an RVM because of the presence of water and other contaminants. [6]

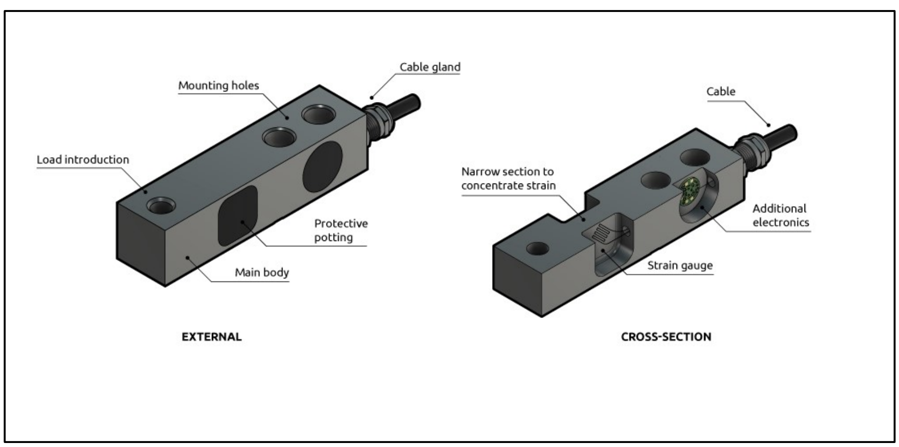


Figure 9: A load-cell

2.2.5. Computer Vision:

This technique employs the use of cameras to gather images of the incoming object. These pictures are then fed into a machine learning algorithm that creates a contour and compares with acceptable bottles. If the bottle is matching, it is accepted, otherwise rejected. [14]

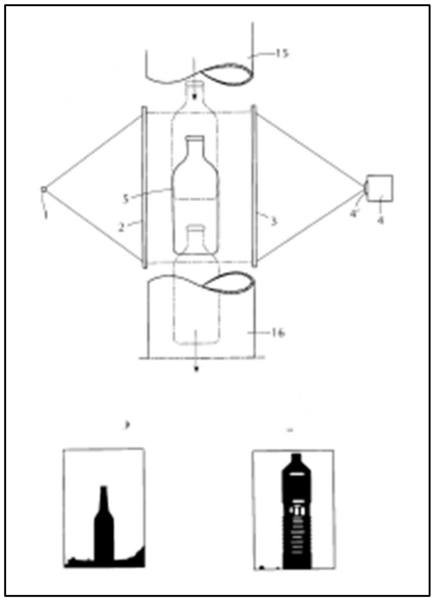


Figure 10: Computer Vision Based sensing

2.2.6. Spectroscopy

Spectroscopy studies the interaction of electromagnetic radiation with different materials. This interaction produces a unique spectrum which depends on the wavelength of the radiation and the material being tested. By bouncing different wavelengths on the material, a spectrum can be generated which is unique for each material. This is because atoms of each element emit and absorb specific wavelengths when their electrons get excited or fall back into their previous shell. Thus, each material will have a unique response to each wavelength depending on the number and type of atoms it contains. [15] [16]

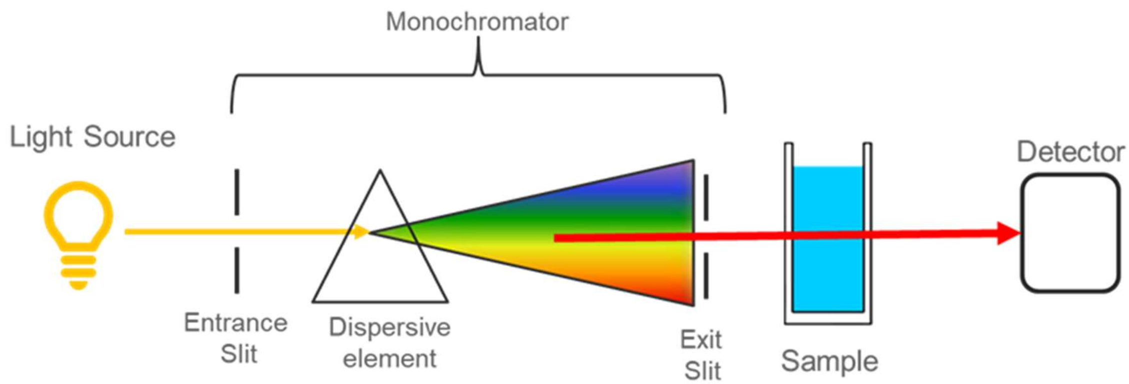


Figure 11: Spectroscopy Method

PET also has a unique spectrum generated by striking different wavelengths at the sample. This is also different from the other types of plastic such as PVC, High Density PolyEthylene (HDPE), Polystyrene (PS) etc. The characteristics of PET can be best distinguished in the Near Infrared (NIR) range of the electromagnetic radiation and referred to as NIR spectroscopy. The difference in the generated spectra can be seen in Figure 12.

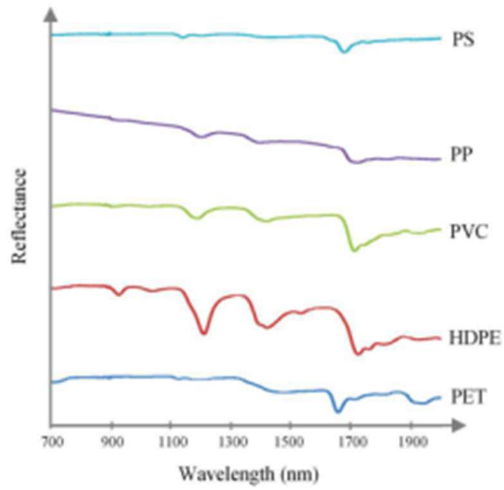


Figure 12: Reflectance Spectra of Various Plastics

The main advantage of using the NIR spectroscopy over other methods is that it can be used to distinguish between all kinds of plastics. The process is rapid and reliable.

2.3. Existing Sorting and Moving Mechanisms

2.3.1. Rotary Chute

In such an arrangement, a rotating chute with holders for plastic bottles is rotated. Plastic bottles are inserted into the holders one by one. The chute rotates and takes the bottles towards the detection module after which they are dropped into either the acceptance or the rejections bins. Several patents were studied which used this concept in one form or another. Most early designs of the RVM use this approach. [17] [18] [19]

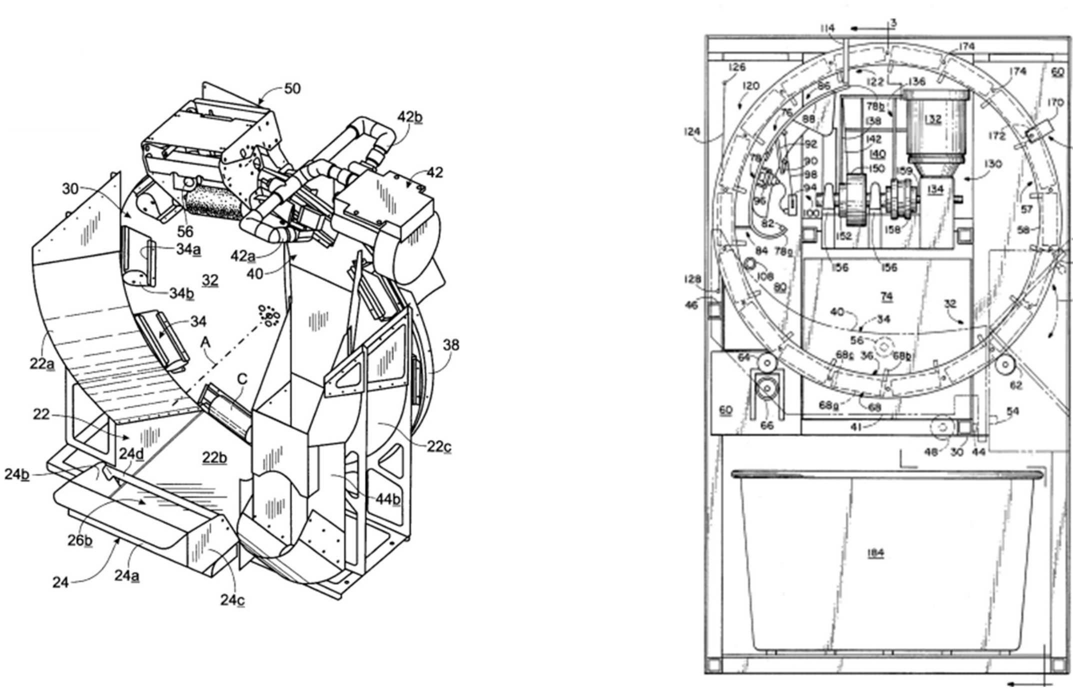


Figure 13: Rotary Chute Based RVMs

2.3.2. Gravity Based:

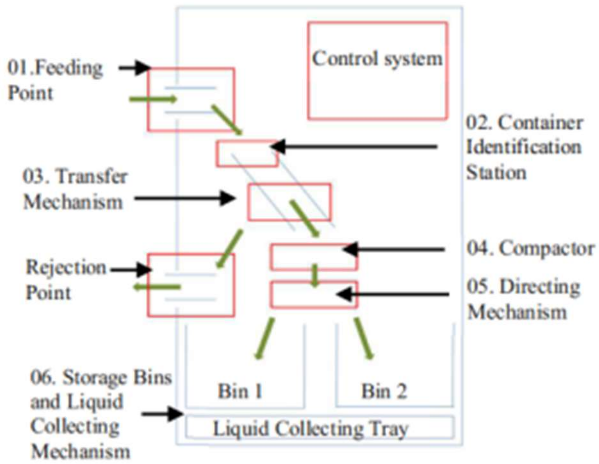


Figure 14: Gravity Based RVM layout.

The method relies on gravity and lets the bottles fall freely. Bottles are detected and classified as they fall. The decision is then used to direct the container towards the appropriate storage. [20]

2.3.3. Conveyor Belt

Some RVM machines use a conveyor belt to transport the beverage containers from their input point to the detection and directing mechanism. These are especially common for machines that handle bulk intake of PET bottles. [21]

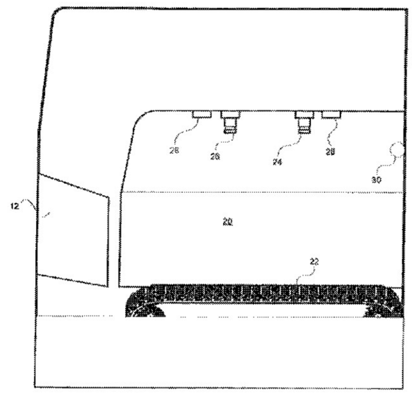


Figure 15: Conveyor Belt Based RVM

CHAPTER 3: METHODOLOGY

The design and fabrication of the proposed reverse vending machine required a thorough surveying of resource availability and local consumer behavior. Several considerations were made for dimension finalization, component selection and material specification. After an extensive literature review, the following four modules of the machine were decided:

1- Intake module (Bulk Feed + Single Feed)

2- Sorting module

3- Sensing module

4- Rejection/Collection module

Details of component and their specifications are mentioned in the research methodology description below.

3.1. System Architecture:

This section entails the overall outlook of the machine showing all integrated systems and their interaction with each other. The sizing, fixature and construction of the complete RVM unit is explained here.

3.1.1. Machine Dimensions

The reverse vending machine is 6 feet long, 6 feet tall and 3 feet wide.

- Length: After two to three design iterations, the inculcation of a separate duct space for the rejected bottles decided the length of the machine which contains five feet of the skeletal frame and 1 feet of the rejection space.

- Height: The machine was designed to be 6 feet tall, which is just a little taller than Pakistani adults' average height. (which turns out to be about 5 ft 4 in when averaged across the genders as well). The height specification makes it possible for the location of the intake points to be conveniently reachable by the majority of users and enable children, adults, and elderly to operate the HMI with equal ease.
- Width: The size of the collection bucket limits the machine's width, and after deciding on its capacity, a round number of 3 feet was chosen.

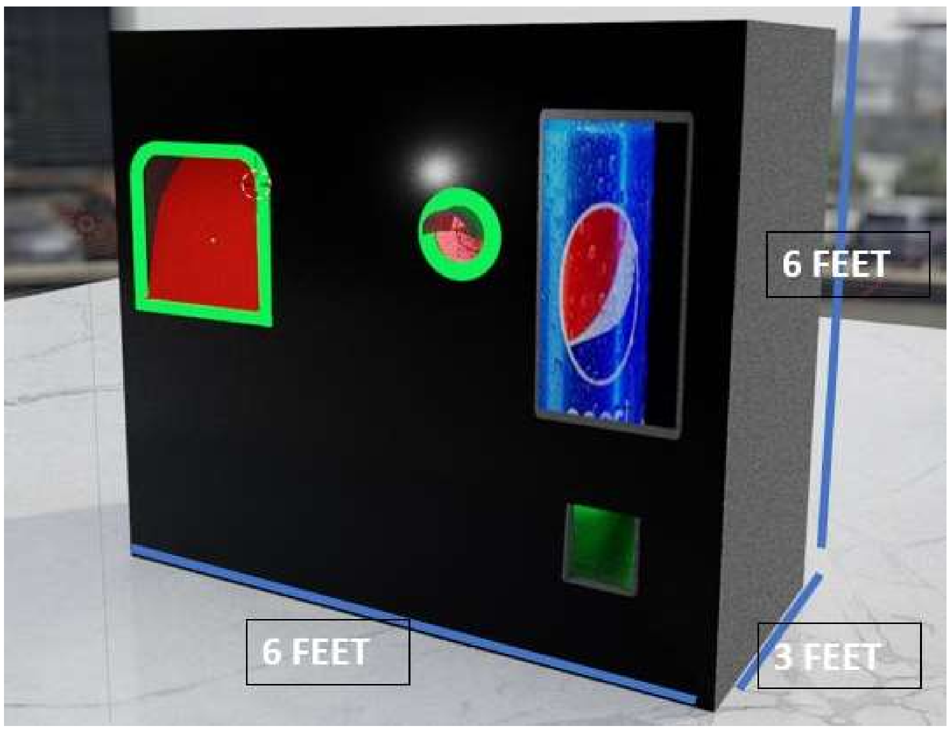


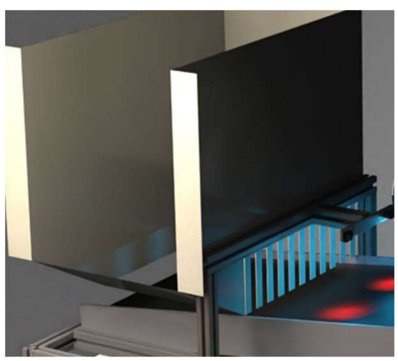
Figure 16 Machine Unit Dimensions.

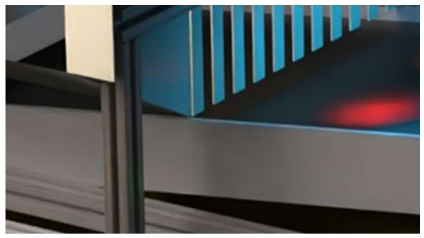
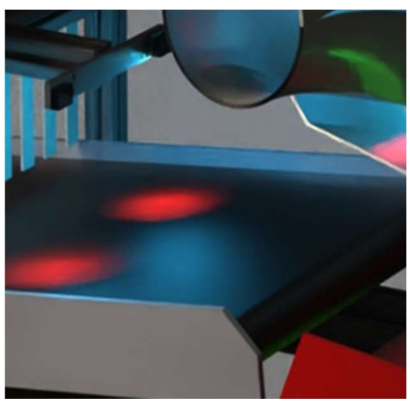
These measurements give the RVM a small, upscale appearance similar to the commonly used vending machines. With this size, the machine can be easily installed in each of its intended places.

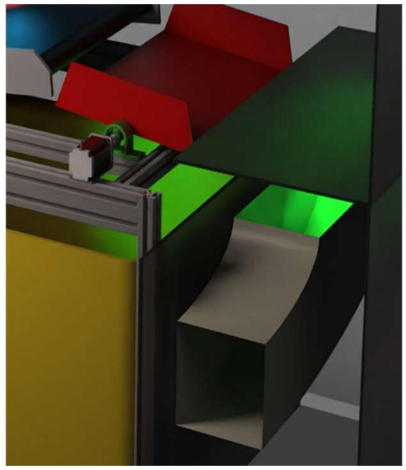
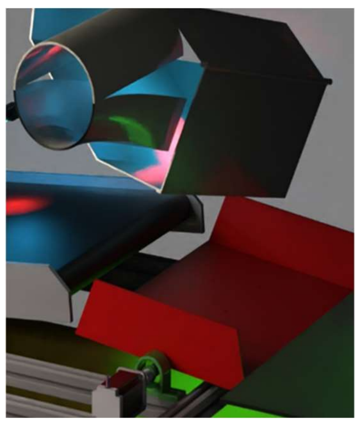
3.1.2. Module placement

Each machine module is positioned with perfect alignment and agreement to ensure the efficiency of the repeated operation. Every part accommodates the location of every other interacting subsystem and helps the required waste collection process to be completed on time. A detailed breakdown of all components contributing to this timed process is listed below:

Table 1 Module placement and Process Optimization.

Module	**Indicating Photograph**	**Stepwise Function Achievement through Design**
Intake Module (BULK)		The bulk feed intake is placed right at the start of the sorting conveyor's platform for the process to start right away once the bulk feed door is closed.
		This is followed by the rubber brushes for separating the containers.
Sorting Module		The upright cleats on the conveyor belt are all spaced about 6 to 8 inches apart for keeping the sorted containers in a

		longitudinal orientation throughout the process.
		The conveyor is elevated at an angle of 8 degrees for: ▪ Effective sorting using gravity. ▪ Gaining elevation for effective subsequent sensing. ▪ Providing for a steep flap angle for efficient rejection and collection.
Sensing Module		The sensing conveyor is perfectly horizontal and is elevated to enough height that its belt is slightly lower than the sorting conveyor's belt and it picks up every container off it and provides a raised, isolated platform for all the sensing operations.
		The photoelectric sensors are installed on an overhead u-truss bridge attached to the skeletal frame sides so that their location can be precisely adjusted.
Collection/Rejection Module		The flap and its shaft are placed right after the sensing conveyor, allowing the PET containers to slide and fall into the bucket

		and the rejected containers to be picked up by the steep flap leading them into the rejection duct through sliding action.
		Collection bucket is placed exactly below the conveyor and the flap stays in the collection orientation during normal operation of the machine so that collection is easy. The flap rotates to the rejection orientation only at rare instances of the detection of a foreign (non-PET) material or a filled PET container.
Intake Module (SINGLE)		This sheet metal manifold, located just above the flap, has an actuated door that opens after sensing and allows the containers to fall onto the flap already positioned into the respective orientation (collection/rejection).

3.1.3. Control system installation

The control system is built into the machine assembly as a network of different sensing, processing, and user-interface devices that are dispersed across the front panel, power compartment, and skeletal frame of the machine.

3.1.3.1. Control Unit:

The rightward portion of the front panel has a sheet metal platform behind it, right above the rejection duct acting as the control unit of the machine.

3.1.3.2.Wiring:

Three types of wiring are included in the machine's design:

- *Panel Power Wiring:* The control system's Arduino, thermal printer and HMI powering wires travel across the internal lining of the front panel.
- *Frame Power Wiring:* The powering wires for conveyor motor, shaft motor, bulk feed door, single feed linear actuator, and the sensors run along the aluminum extrusion lengths of the skeletal frame.
- *Serial Communication Wiring:* Motor driver modules, sensors and the HMI communicate with the PLC through jumper wire connections travelling across the skeletal frame and the side, front and back panels as per the need.

3.2. Process Calibration and Engineering Considerations:

The process calibration for a reverse vending machine is crucial to ensure its smooth and efficient functioning. In this regard, the sizing of the sorting conveyor, the angle of the flap's collection and rejection orientations, the opening of single feed compartment's play a significant role in the process.

This design ensures that the rejected items are quickly and effectively diverted away from the accepted containers, minimizing the chances of any contamination. The elevated and isolated platform provided by the sensing conveyor also helps in accurately sensing and identifying each container. The details of these engineering considerations are mentioned below.

3.2.1. Sorting Belt

The sorting belt has cleats (rubber strips) on its surface ensuring that the containers travel one by one. The spacing between has been designed according to the diameter of large PET containers with a little space included for preventing any containers getting stuck.

Calculations are as follows:

Largest PET container (2.25 L bottle) diameter = 4.33 inches

Cleat spacing = 6 inches

Moreover, the sorting conveyor has been inclined at an angle of 8 degrees after testing. At this angle, a filled bottle (weighing about 2 kilograms) does not fall off the belt and any stacked-up containers fall back for coming up in some other empty inter-cleats space.

The dimensioning details for providing the sorting conveyor with an 8-degree elevation at one end are shown in the diagram below:

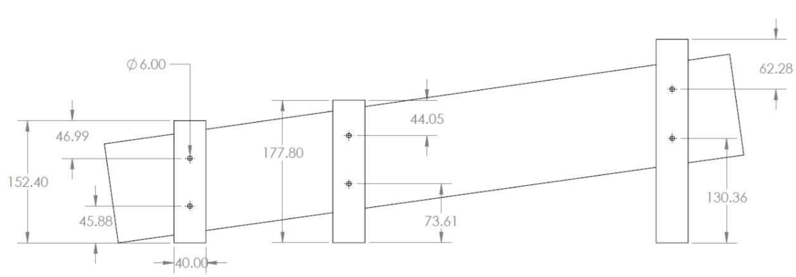


Figure 17: Conveyor elevation fixture dimensions.

The conveyor's width of minimum **20 inches** was limited by the maximum length of a 1.5-liter PET bottle of about **18 inches** with a slight margin for prevention of collisions.

3.2.2. Sensing Station

The sensing station (small conveyor) has been fixed in a horizontal orientation according to the sensor's working area requirement. The height of the sensing conveyor has been calculated according to the rejection orientation of the flap (tilted at an angle of $\leq$ 45 degrees with the horizontal).

The load cell has been placed under the sensing station and calibrated so that it neglects the sensing conveyor's weight and indicates incremental container loads on the sensing belt.

3.2.3. Actuated Single Feed Door:

The single feed door operates via a linear actuator hinged to its inner surface and its fixture location has been calculated such that the actuator's stroke opens the door to an extent that it at least allows the largest available PET container to slide or roll through the opening onto the flap with ease.

The calculations are as follows:

3.3. Mechanism Design and Fabrication

3.3.1. Conceptual Design

The conceptual design of the RVM, or Reverse Vending Machine, involves creating a user-friendly and efficient system for collecting and recycling used beverage containers. The RVM would incorporate a system in which a user inserts a plastic container into the machine, it would be scanned and identified, and then the appropriate deposit refund would be calculated and dispensed to the user. Overall, the conceptual design of the RVM aims to incentivize recycling and reduce waste, making it an important tool for promoting environmental responsibility.

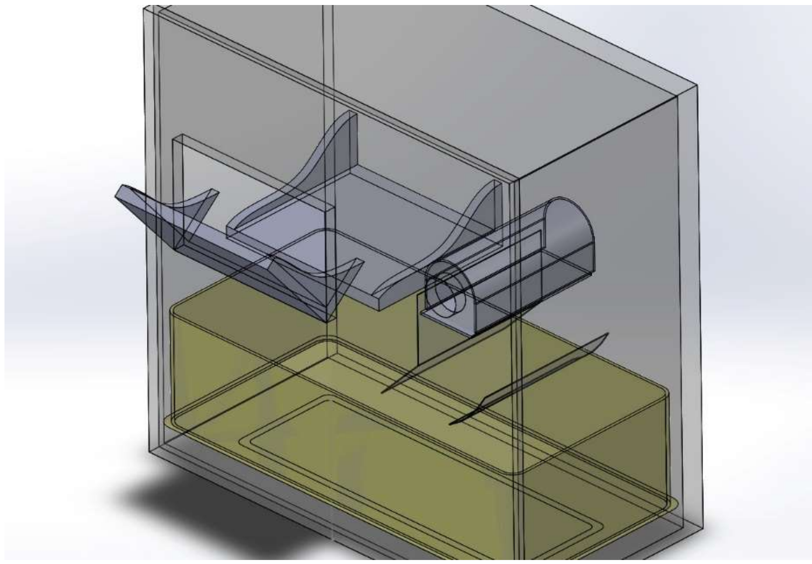


Figure 18: Conceptual Design

3.3.2. Virtual Design Iterations

The design iterations were performed on Solidworks, and 3D models were created, using which the design of the machine was optimized throughout the iterative process. This was done so that the RVM's 3D model can be visualized and tested virtually, enabling the identification of potential issues and improvement of the design before building physical prototypes. This process enabled the exploration of various design alternatives regarding the placement of sensors and motors, the shape and size of the collection bin, and the layout of the user interface. Overall, it was a critical step in the development of the RVM, allowing the creation of an efficient and reliable machine that can effectively collect and sort recyclable materials.

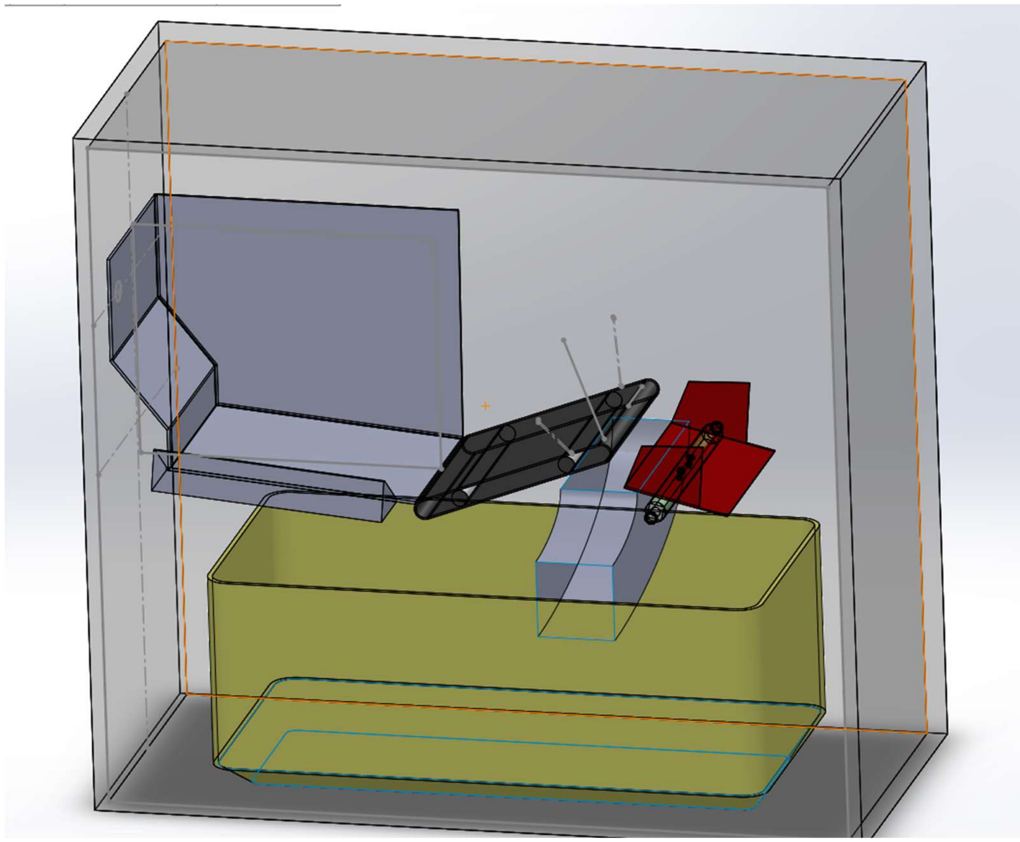


Figure 19: Iteration 1

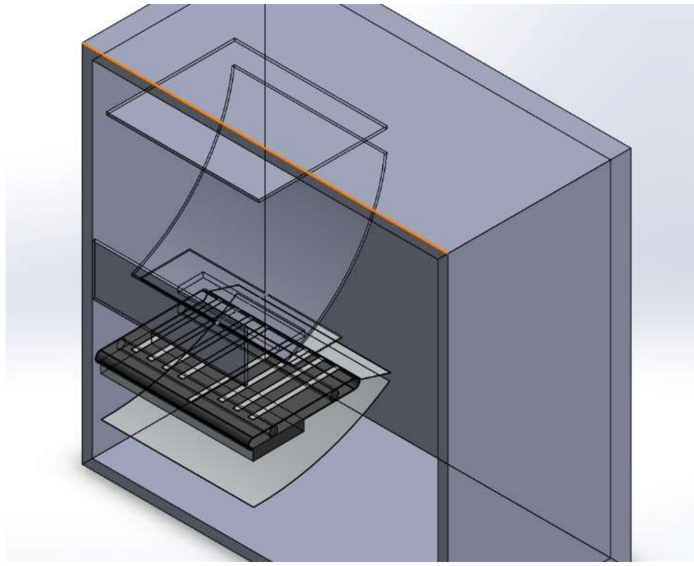


Figure 20: Iteration 2

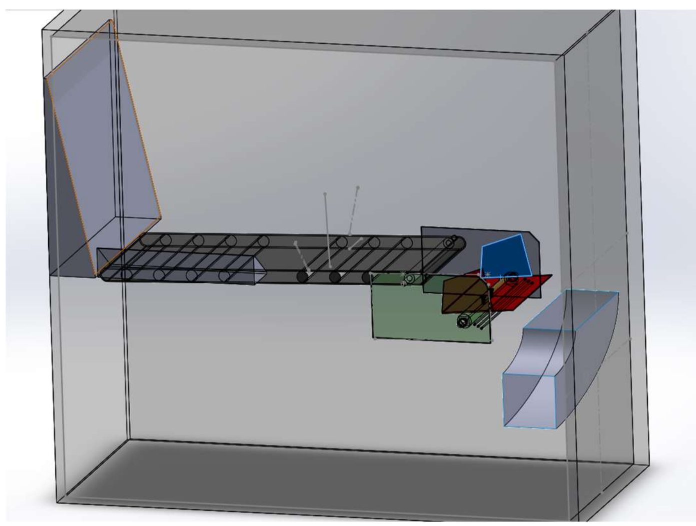


Figure 21: Iteration 3

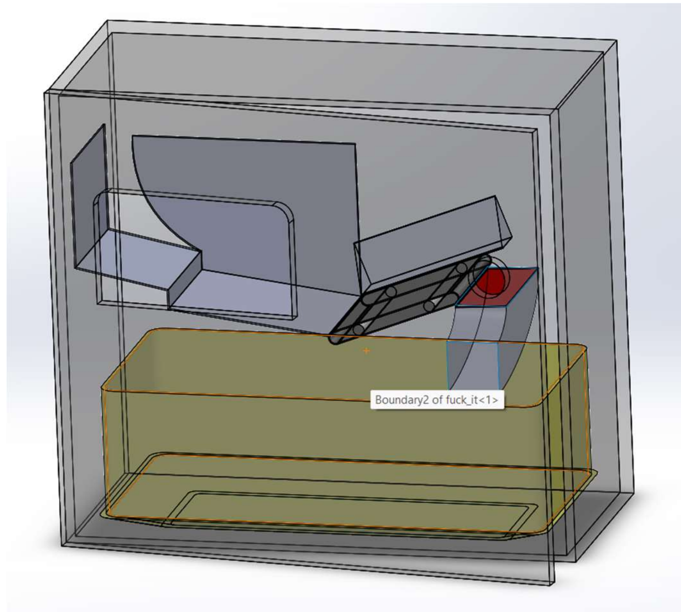


Figure 22: Iteration 4

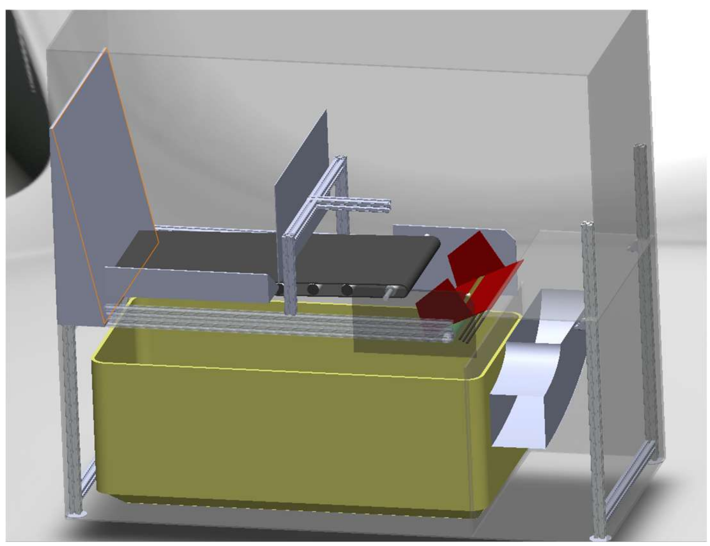


Figure 23: Iteration 5

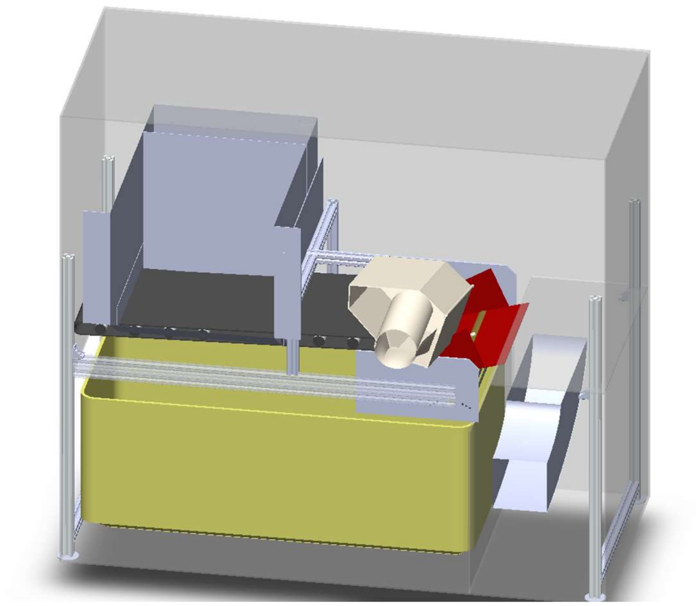


Figure 24: Iteration 6

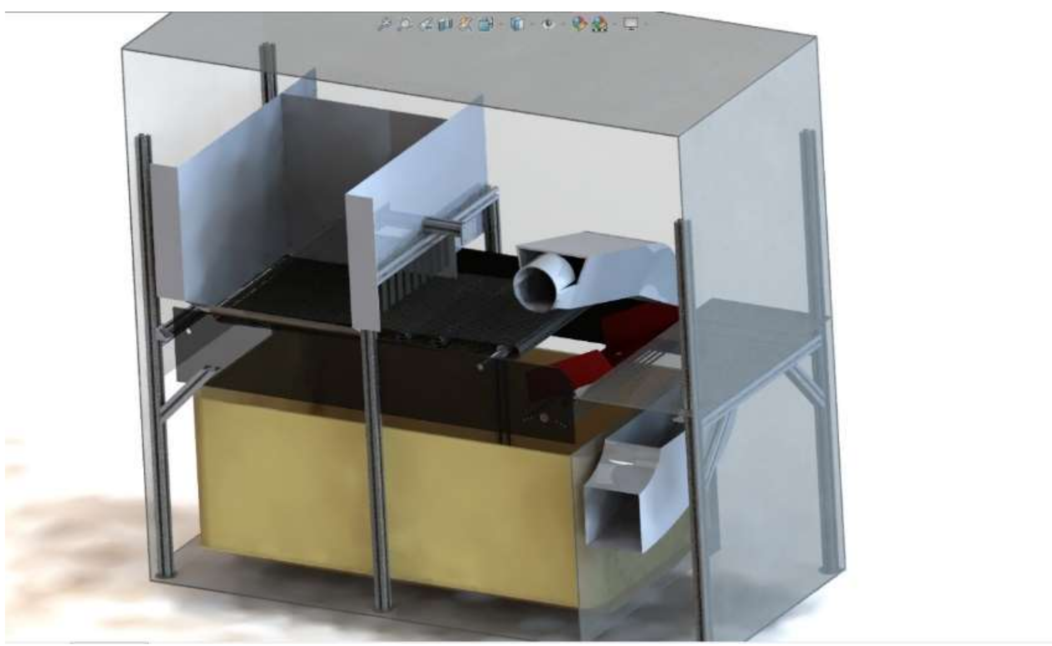


Figure 25: Iteration 7

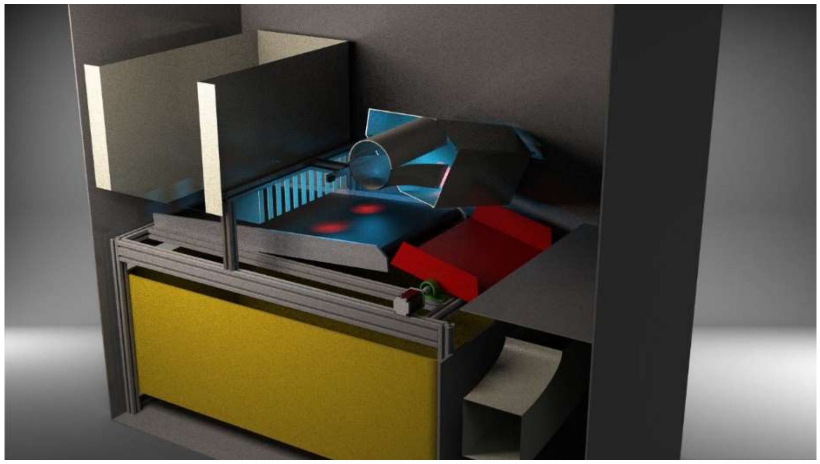


Figure 26: Iteration 8

3.3.3. Components Selection

The components were selected by consulting the respective components catalogues and engineering mechanics and materials calculations.

i. Structural frame.

Aluminum extrusions were used to design the structural members of the machine, which includes the frame and the conveyor mounts. Their cross-sectional dimensions were selected based on the loadings applied on them. Another reason for using them was that they allowed the structure to be made with mechanical fasteners which could be repositioned if needed to ease up the prototyping process.

ii. Bearings.

Bearings were used to simply support the shaft for the flap mechanism, they were selected based on the loadings and the optimal shaft diameter calculated. Their selection was done using the NSK catalogue.

iii. Bolts and nuts

A standard was used for the bolts and nuts, according to which we selected M6 to be the optimal bolt and nut diameter and we used this standard throughout machine assembly.

iv. Casing

The casing was made using the 1mm thick sheet metal of Mild Steel (MS). It was chosen considering the optimization between the structural integrity, cost and strength of the material.

v. Intake compartments

The compartment for the single intake and the sorting chamber of the bulk intake modules were made using the 1mm thick sheet metal of Mild Steel (MS), this was selected keeping the load considerations in check.

vi. Rejection duct

A 1mm thick sheet metal of Mild Steel (MS) was used to make the rejection duct, the structural integrity and manufacturing feasibility were considered for this selection,

vii. Bucket

A plastic bucket was chosen for this purpose as it reliable for long term use-age and it is readily available in the local market and offers great resistance to chemical contamination.

3.3.4. Manufacturing techniques.

i. Intake module

The intake module consists of two components, i.e. the single intake and the bulk feed intake respectively, sheet metal has been used to manufacture them. Processes like bending, riveting, welding cutting were used to shape them into the desired engineered compartments.

ii. Sorting module

The sorting module consists of a conveyor mounted on the frame passing from the bulk feed intake to the sensing module. It was made using ABS plastic, PVC pipes and rubber belts. The ABS plastic was used to make the structure with the help of super glue, and the rollers were made using PVC pipes and the rubber belts were used to make the belt and the cleats for the conveyor belt.

iii. Sensing module

The sorting module consists of a smaller conveyor mounted on the frame, after the sorting conveyor and just before the flap mechanism. It is also made using the same procedure as the sorting conveyor.

iv. Rejection/Collection module

This comprises of the flap mechanism that either directs the feed into the collection bucket (acceptance) or to the rejection duct (rejection), it consists of a shaft that is simply supported by two bearings, the shaft is machined to our desired dimensions and then end mill operation has been performed on it to flatten its cylinder surface of it so that the flap can rest on it. The flap is made from a 2mm sheet of sheet metal of Mild Steel (MS).

3.4. Machine Assembly

The machine was made using different assembly techniques for various components to work in cohesion with each other seamlessly.

3.4.1. Mechanical Fastening

We used mechanical fastening at various places to make the design more modular and easier to perform maintenance upon. The following are the places where we used mechanical fasteners.

i. Corners joints

We used the 90-degree corner joints in the frame to join aluminum extrusions with each other perpendicularly to make the desired frame geometry.

ii. Lap joint

The lap joints were used to mount the motor on the Aluminum frame. The motor gets mounted on the lap joint, and the lap joint is then mounted on the Aluminum frame. This was done to effectively make the flap mechanism.

iii. Bolting

We used a standard of M6 diameter for our bolts and nuts, we attached the conveyor, the mountings, the Aluminum corners and in Aluminum extrusions to hold everything together while making the assembly and disassembly convenient for prototyping purposes.

iv. Riveting.

Riveting was performed for the sheet metal of the casing as well as the intake modules to fasten them in the desired shapes as per the engineering design.

3.4.2. Adhesive fastening

Adhesive fastening was used at the places where structural strength and integrity was important, and the feasibility of prototyping and assembly disassembly of other components was not disturbed.

i. Welding

Welding was performed on the casing of the sheet metal to give it a cuboidal shape, structural strength and the desired sealing and also so that anyone may not open the machine in any way for stealing. Welding was also performed on the mounting of the single intake module and the sorting chamber on the casing.

3.5. Control Systems

3.5.1. Sensor selection and data acquisition

In order for the machine to operate, it needs to collect information about the objects inside the machine. This is done using sensors.

3.5.1.1. Spectral Colour Sensor (AS7341)

The AS-7341 is an 11 channel spectral colour sensor which is capable of giving highly accurate object colour measurements. It is highly cost effective. The 11 wavelengths of the spectral sensor lie in the visible-near infrared range (Vis-NIR) between 350-1000nm. [22]

The sensor works by measuring the intensity of radiation of each wavelength reflected from the material into the sensor.

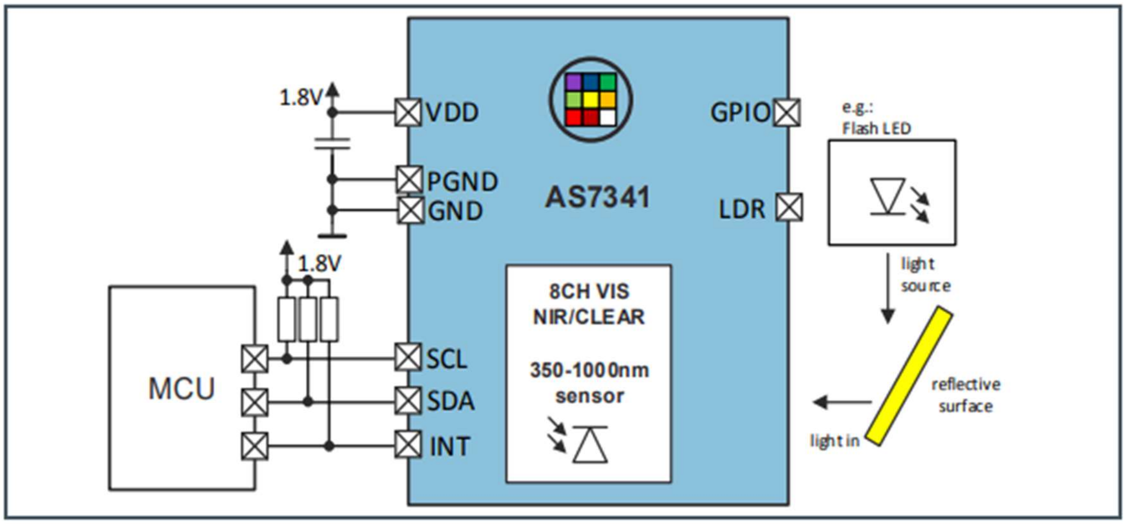


Figure 27: Working of AS7341 Spectral Sensor

Calibration of this sensor is carried out by following the guidelines given in the datasheet. [23]

3.5.1.2. Load cell

For added sensing accuracy, another sensor is added to differentiate plastic bottles from other common clear objects, like glass. The working principle here is that glass is much heavier than plastic. This will also differentiate and reject filled plastic containers from empty plastic containers due to the difference in weight.

Load cells employ a strain gauge, and its resistance varies with the applied loading due to increase in length of the wire. This results in a voltage which varies with applied loading.

3.5.1.3. Proximity sensor

The machine needs to always know, if there is an object present or not. This is important because the machine needs to know that objects are still coming from the conveyor belt despite the other sensors being in the low state due to the object being clear and lightweight, which can only mean that the object is a clear, plastic bottle.

A capacitive sensor will be employed to carry out this task. The way it works is by emitting an electric field, which when disrupted by any object, will be detected by the capacitive sensor. We will be using the NPN type sensor, which will be connected directly to the PLC.

The sensitivity can be adjusted to meet specific application requirements, but our purpose requires the sensitivity to be at its maximum setting.

3.5.1.4. Limit switch

Since we are using a relay type PLC, it is best way to monitor the position of the flap is to employ limit switches rather than using timer functions to notify the plc when the flap has reached the extreme position, so it can turn the stepper motor off. The switches will be installed at the extreme positions of the flap. The limit switch used is the ‘Moujen ME-8104’. It is a single pole-double throw switch (SPDT) which allows for switching of one circuit operation as opposed to double pole double throw (DPDT) switches, which can switch multiple switches. The internal circuitry of the ME-8104 is given below:

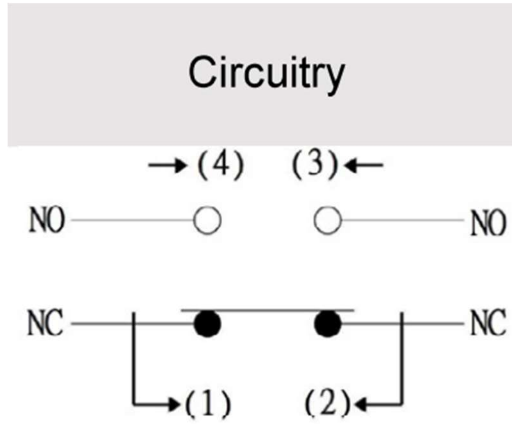


Figure 28: Limit Switch Circuitry

Another limit switch will be used to monitor the position of the feed. The RVM can only operate with the feed in the closed position.

3.5.2. Actuator selection

3.5.2.1. Linear actuator

The linear actuator is installed perpendicular to the foot of the single feed opening. Its purpose is to actuate, after the bottle has been verified to be a clear plastic bottle, via the sensors.

3.5.2.2. Stepper motor

The stepper motor is connected to a flap mechanism which moves from its default position depending on the state of the sensors that govern the type of object present. The motor is to move the flap such that the clear plastic bottles are dropped and deposited in the acceptance bin. Otherwise, the flap remains in its default position and the object is sent back to the user through the rejection chute.

The stepper motor used is the NEMA 23. This is a two-phase motor.

This motor is wired to the TB6560 motor driver, to which 24 VDC is supplied the ‘Weidmüller 8708660000’ power supply. Pulse signal comes from a pulse card, which employs the NE555 chip. This chip is to be powered by the PLC (programmable logic controller). This chip sends a square wave, and its duty cycle and frequency can be adjusted by turning the knobs using a flathead screwdriver.

By default, the chip is powered off. When the flap position needs to be changed, stepper motor operation is required, and the chip needs to turn on in order to send the pulse signal. For the motor to move back to its required position, a constant supply of 5 VDC needs to be supplied to the DIR+ of the driver, using the PLC. Wiring is as follows:

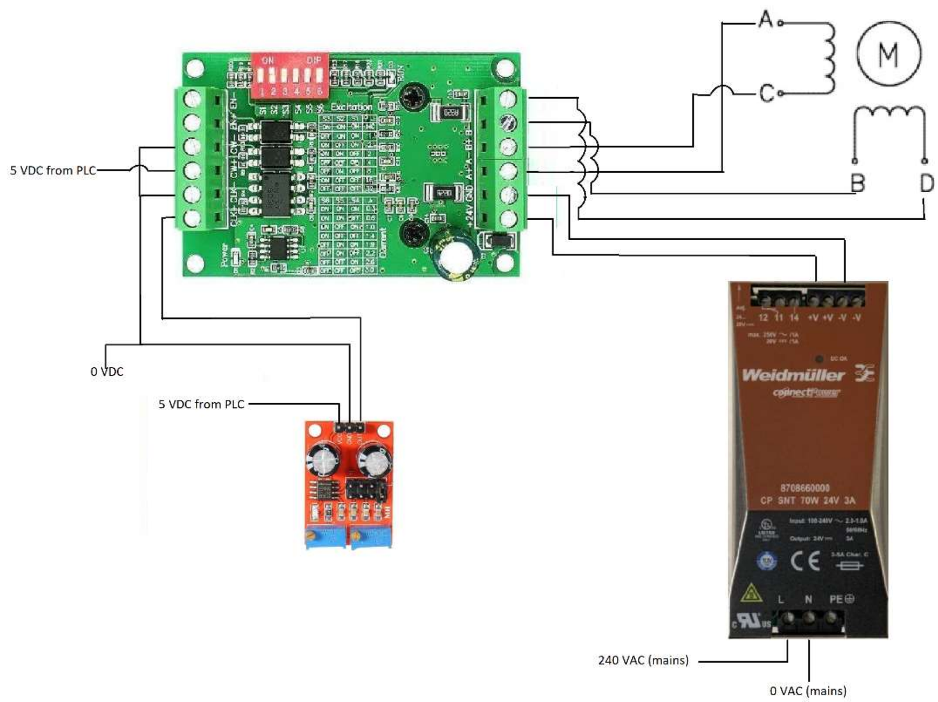


Figure 29: Wiring of motor driver.

3.5.3. PLC programming and control

3.5.3.1 PLC (Programmable logic controller)

The controller used in our machine will be the DELTA DVP20SX2.

It features 20 points:

- 4 AD (analog to digital) input points
- 2 DA (digital to analog) output points
- 8 digital input points
- 6 digital output points

It is powered using 24 VDC.

3.5.3.2.Programming software

DELTA products can utilize one of two programming softwares, WPLSoft or ISPSoft. We have chosen to use WPLSoft as it offers all the required programming features.

3.5.3.3.Developed program.

The program developed is a simple to understand, yet logical and powerful ladder diagram which utilizes normally open/closed contacts, timer functions, switching of auxiliary relays to switch parts of the ladder diagram.

In our program, for example, when bulk feed is selected, auxiliary relay M2 is set. When the bulk feed limit switch is closed the following segment will set auxiliary relay M1, which is used to control the motor.

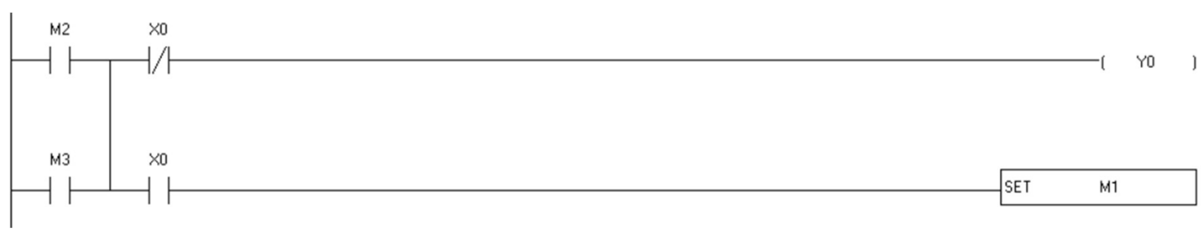


Figure 30: Sample Ladder Logic Program

3.5.4. Control flowchart

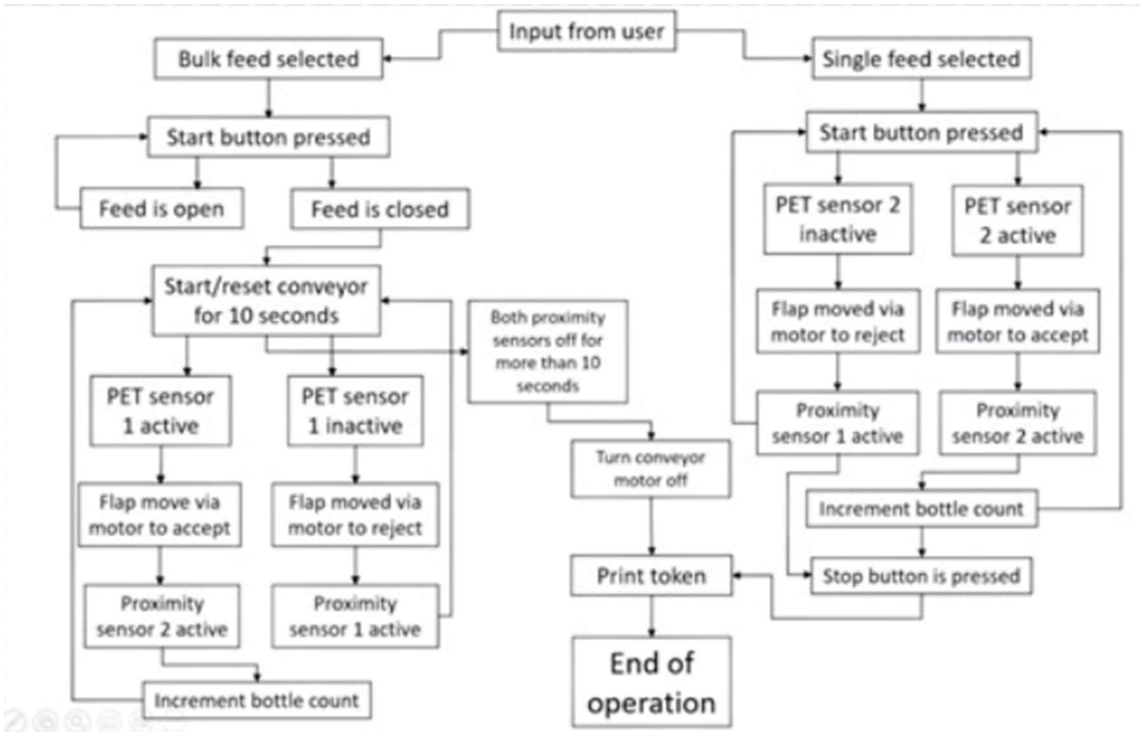


Figure 31: Control Flowchart

3.5.4.1.Wiring diagram

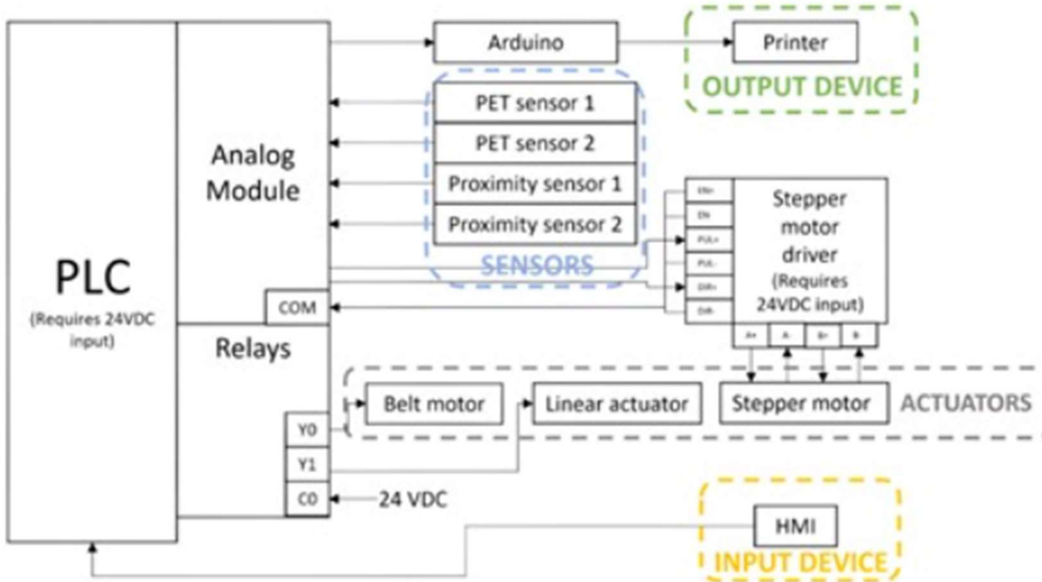


Figure 32: Wiring Diagram

3.5.5. User interface design

3.5.5.1.HMI (human machine interface) selected:

The HMI used is the NEXTION NX3224T024. It is a 2.4 inch model featuring a touch screen.

Since said HMI does not feature any documentation regarding MODBUS, we have decided to interface the Nextion with an Arduino using serial communication and depending on the input received from the HMI, PWM pins on the Arduino will be used to set to a varying voltage and sent to a single channel of the AD (analog to digital) card of the PLC. The PLC will be programmed to do different things based on the voltage of the signal sent.

For example, if 2.5 volts is sent to the PLC, an auxiliary relay is set. If 5 volts is sent, then an auxiliary relay is reset.

3.5.5.2.Software used.

Nextion Editor was used to program the Nextion display.

Arduino IDE was to code in C++, using the Nextion library from the official website.

3.5.5.3.Programming of the Nextion display.

In the Nextion editor, a global variable is defined. This variable has the value of 1 when the bulk feed is open. When either bulk feed or single feed is selected, the user is taken to a different page which notifies the user to close the feed.

When the feed is closed, the value of the variable is changed to 0 and the user is taken to a different page, and the through serial communication the value of a different PWM pin set (2.5 V_{DC}, single feed and 5 V_{DC}, if bulk feed) and sent to a different AD channel of the PLC.

The Nextion is also programmed to display the bottle after the operation has finished.

3.5.6. Printer

The printer is linked to the Arduino via serial communication and utilizes the Adafruit library. It is powered using a 9 V_{DC} and 3 Amperes for reliable operation.

3.6. Calculations

3.6.1. Shaft Calculations

The following calculations are being done assuming a Factor of Safety (FOS) of 1.5 and material is aluminum whose yield strength is 200MPa.

Minimum Diameter for Bending Load

Following formula can be used to calculate the minimum shaft diameter using only bending load:

$$d = \sqrt[3]{\frac{32M_b \times FOS}{\pi \times Yield\ Strength}}$$

Assuming a 3kg bottle hitting at flap end, a Factor of Safety (FOS) of 1.5

$$M_b = 30N \times 0.33m = 9.9Nm, \qquad Yield\ Strength = 200MPa$$

$$d = \sqrt[3]{\frac{32 \times 9.9 \times 1.5}{3.142 \times 200 \times 10^6}}$$

$$d = 0.9\ cm$$

Minimum Diameter for Torsional Load

$$d = \sqrt[3]{\frac{16M_t \times FOS}{\pi \times Yield\ Strength}}$$

Considering the motor torque of 3.2Nm (NEMA 23)

$$M_t = 3.2Nm, \qquad YS = 200MPa$$

$$d = \sqrt[3]{\frac{16 \times 3.2 \times 1.5}{3.142 \times 200 \times 10^6}}$$

$$d = 0.49\ cm$$

Minimum Diameter considering Shear Stress under combined loading

$$d = \sqrt[3]{\frac{16}{\pi \times \frac{Yield\ Strength}{2 \times FOS}} \times \sqrt{M^2 + T^2}}$$

$$d = \sqrt[3]{\frac{16}{\pi \times \frac{200 \times 10^6}{2 \times 1.5}} \times \sqrt{9.9^2 + 3.2^2}}$$

$$d = 0.93cm$$

Minimum Diameter considering Normal Stress under combined loading

$$d = \sqrt[3]{\frac{16}{\pi \times \frac{Yield\ Strength}{FOS}} \times (M + \sqrt{M^2 + T^2})}$$

$$d = \sqrt[3]{\frac{16}{\pi \times \frac{200 \times 10^6}{1.5}} \times \left(9.9 + \sqrt{9.9^2 + 3.2^2}\right)}$$

$$d = 0.93cm$$

3.6.2. Aluminum Extrudes

The aluminum extrudes used in the foundation table are of two types. The 4080 beams of 150cm are sustaining bending load whereas the 4040 beams are sustaining axial load.

Maximum load bearing capacity for bending beams

Part Number			Height x Width (mm)	Section Modulus x 10^3 (mm^3)	Cross Sectional Moment of Inertia x 10^4 (mm^4)	For 500mm Extrusion Length		For 1000mm Extrusion Length	
Type	Extrusion					Allowable Load		Allowable Load	
						(N)	(kgf)	(N)	(kgf)
HFS5 NFS5	2020	(1)	20x 20	0.74	0.74	99	10	24	2
	2040	(2)	20x 40	1.35	1.35	182	18	45	4
		(3)	40x 20	2.55	5.11	687	70	171	17
	2060	(4)	20x 60	1.97	1.97	264	26	66	6
		(5)	60x 20	5.32	15.96	2144	218	536	54
	2080	(6)	20x 80	2.58	2.58	347	35	86	8
		(7)	80x 20	9.02	36.11	4851	494	1212	123
	2525	(8)	25x 25	1.36	1.71	229	23	57	5
	2550	(9)	25x 50	2.37	2.96	398	40	99	10
		(10)	50x 25	5.09	12.74	1711	174	427	43
	4040	(11)	40x 40	4.45	8.9	1196	122	299	30
	4060	(12)	40x 60	6.3	12.62	1695	172	423	43
		(13)	60x 40	9	27	3627	369	906	92
	4080	(14)	40x 80	9.18	18.38	2469	251	617	62
		(15)	80x 40	15.87	63.49	8529	869	2132	217
HFS6 NFS6	3030	(16)	30x 30	1.89	2.83	381	38	95	9
	3060	(17)	30x 60	3.55	5.33	716	73	179	18
		(18)	60x 30	6.84	20.53	2758	281	689	70
	3090	(19)	30x 90	5.62	8.43	1133	115	283	28
		(20)	90x 30	14.71	66.19	8892	906	2223	226
	6060	(21)	60x 60	13.78	41.35	5555	566	1388	141
	6090	(22)	60x 90	17.53	52.59	7065	720	1766	180
		(23)	90x 60	24.77	111.5	14979	1527	3744	381
	30120	(24)	30x 120	7.52	11.29	1516	154	379	38
		(25)	120x 30	25.55	153.3	20595	2100	5148	525
	60120	(26)	60x 120	23.06	69.18	9294	947	2323	236
		(27)	120x 60	41.18	247.1	33196	3385	8299	846
	5050	(28)	50x 50	8.66	21.66	2909	296	727	74
	50100	(29)	50x 100	16.98	42.44	5701	581	1425	145
		(30)	100x 50	30.63	153.2	20581	2098	5145	524
	100100	(31)	100x 100	53.08	265.4	35655	3635	8913	908
	4040	(32)	40x 40	5.24	10.48	1407	143	351	35
	4080	(33)	40x 80	9.95	19.91	2674	272	668	68
		(34)	80x 40	18.07	72.26	9707	989	2426	247

Figure 33: Load Capacity Calculations for Aluminum Extrudes

Extrapolating from the table

$$\frac{500}{1000} = 2, \qquad \frac{9707}{2426} = 4$$

This shows that doubling the extrusion length reduces maximum load capacity by a factor of 4. Thus, increasing length by a factor of 1.5 results in maximum load capacity decreasing by $1.5^2 = 2.25$. As the length of the foundation table is 150cm, the maximum load capacity is found as

$$F_{max} = \frac{2426}{2.25} = 1078N$$

This calculation has been done for the 4080 aluminum extrudes which form the foundation of the structure. The load capacity is well above the required load bearing capacity of 500N.

Maximum load bearing capacity for axially loaded beams

The load required to cause a certain deflection of an axially loaded beam can be found by the following formula:

$$F = \frac{EA\Delta l}{l}$$

The length of each supporting leg of the foundation table that bears the axial load is 75cm. Assuming a 1mm deflection to be the failure criterion, the maximum axial load for each leg is calculated to be

$$F = \frac{69972 \times 640 \times 1}{750} = 59709N$$

This is the maximum axial loading for only one leg which is comfortably within the required maximum loading capacity.

3.6.3. Actuated Single Feed Door

Here we do the calculation for the stroke length of the linear actuator to allow single feed bottles to leave the sensing area.

Largest PET container (2.25 L bottle) diameter = 4.33 inches

Maximizing this to 6 inches.

S_b = Effective opening arc length = 6 inches = 152.4 mm

Now

$$S_b = r\theta$$

Where r is the length of the single feed door plate.

$$r = 212.8 \text{ mm}$$

Hence,

$$\theta_{req} = 0.71616 \text{ rad}$$

Maximizing:

$$\theta_{req} = 45^{o}$$

For calculating the door plate moment arm l_p (distance between the door hinge and the actuator hinge on the single feed door acting as the effective radius for the door),

Assuming the full stroke of the linear actuator creates the required opening.

Linear Actuator Full Stroke = $S_{1\,max}$= 95 mm

Now,

$$S=r\theta$$

$$S_{1\ max}=l_{p\ f.s.}\theta$$

$$95\ mm=l_{p\ f.s.}\times\frac{\pi}{4}$$

$$l_{p\ f.s.} = 120.95\ mm$$

Assuming about half (45 mm) stroke of the linear actuator creates the required opening.

Hence,

$$l_{p\ final} = ?$$

$$45\ mm = l_{p\ final} \times \frac{\pi}{4}$$

$$\boldsymbol{l_{p\ final} = 57.3\ mm}$$

CHAPTER 4: RESULTS AND DISCUSSIONS

We were successful in manufacturing a working prototype of the RVM consisting of both a single feed and bulk feed mechanism. The results of the project are very encouraging. The machine is ergonomic and cost-efficient.

The isometric and side view of the machine are as follows:

Figure 34: Side View of the RVM

Figure 35: Isometric View of the RVM

The accuracy of the various assemblies and the analysis is done separately and collectively.

4.1. Foundation

The foundation table made of 4080 and 4040 aluminum extrudes is supposed to provide stability and support to the all the other components. It is also the element prone to vibrations from the motors and actuators. The foundation easily withheld the weight off the components and did not cause any issues.

4.2. Single Feed Assembly

The single feed assembly comprising of the sensing area and the actuated door was very accurate in its operation. It was programmed to open after the sensing and the decision (acceptance or rejection) had been made. The timing of the opening was always accurate. In a few iterations, some bottles got stuck and did not fall off. It was attributed to some improper machining and bumps which were rectified, and the operation became smooth. The single feed assembly was connected to the foundation table using wood for prototyping purposes. The wood also withheld the weight of the single intake well. The single feed assembly is working as expected.

4.3. Bulk Feed Assembly

The Bulk Feed assembly consisted of an intake hopper, cleated conveyor and screen that converts bulk intake into individual bottles making it easier for sensing. The conveyor incline angle of 8° and the cleats worked well to ensure that the bottles entered the sensing conveyor individually. Some anomalies were seen in the operation as the bottles left the conveyor at an inappropriate angle for sensing. However, the operation was largely accurate.

4.4. Sensing

The sensing required the calibration of the Vis-NIR spectroscopy sensor. This was done by testing the sensor for various materials and tabulating the results. The sensor was found to be sensitive to ambient lighting conditions. The sensing area was thus encapsulated to ensure efficient operation.

The combination of wavelengths for PET was found to be unique from all other materials tested. The combination was thus used to program the decision of the sensing. Upon operation, the algorithm was found to be largely accurate with an accuracy of 92% during operation. The inaccuracy can be mostly attributed to the dependency of the sensor on the lighting conditions. Coloured PET bottles also showed anomalous behaviour giving an accuracy of 78% under normal operation. This was due to the presence of different pigments in the coloured PET. The sensor was then re-calibrated to include the coloured PET range and the accuracy was enhanced to 89%.

4.5. Decision and Collection Mechanism

The mechanism consisting of motor, shaft and flap was controlled using the PLC when the decision was made after the information was received from the sensor. The motor operation was fast, robust and accurate. Some initial problems of the motor angle adjustment were catered for by homing the motor through limit switches.

4.6. Discussion

The machine presents satisfactory results of accuracy considering it is a prototype. Accuracy can be improved by making changes which will be discussed in the recommendations. The methodology used for the project is to provide a cost-efficient solution for prototyping purposes. Better sensing and conveying technology can be used in the actual machine for better results.

Other sensing options such as the employment of computer vision can give highly accurate results as high as 99%. In comparison, the accuracy of the current sensing method is lower.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

The developed Reverse Vending Machine plays a pivotal role in significantly reducing plastic waste. With its affordable price, this machine becomes an ideal solution for businesses seeking a sustainable and cost-effective approach. The machine boasts an exceptional bottle classification mechanism, ensuring accurate sorting and recycling. Moreover, its ergonomic design adds convenience to the user experience.

In addition to its remarkable functionality, the Reverse Vending Machine boasts minimal energy requirements, making it an energy-efficient choice. Furthermore, its lightweight construction enhances mobility, allowing for easy relocation as needed. These features make the machine versatile and adaptable to various settings.

With ongoing design iterations, the prototype can be further refined to meet market demands. Addressing user feedback and incorporating improvements will enhance its usability and efficiency. By continuously enhancing the machine's design, it can evolve into a highly sought-after product in the recycling industry.

The successful development of this Reverse Vending Machine project has not only addressed the urgent issue of plastic waste but has also opened up new possibilities for future advancements in the field. It serves as a stepping stone for further research, innovation, and sustainable solutions. As society becomes increasingly aware of the importance of recycling, this machine paves the way for a greener and more environmentally conscious future.

5.2. Recommendations

Here are some recommendations for improvements that can be made in future iterations of the Reverse Vending Machine:

1. Enhanced Bottle Recognition: While the machine already has an accurate bottle classification mechanism, there is room for improvement. Research and development efforts should focus on advancing the machine's ability to recognize a broader range of bottle types, including different materials, shapes, and sizes. This will ensure more efficient sorting and recycling processes. Computer Vision can be integrated into the machine to improve accuracy.
2. Increased Capacity: To accommodate higher volumes of plastic waste, future iterations should aim to increase the machine's capacity. This can be achieved by optimizing the internal storage system or incorporating larger storage compartments. Increasing the machine's capacity will minimize the frequency of emptying and improve overall operational efficiency.
3. Integration of Smart Technologies: Consider integrating smart technologies, such as Internet of Things (IoT) connectivity and data analytics, into the machine. This will enable real-time monitoring of machine performance, collection levels, and operational metrics. By gathering and analyzing this data, businesses and

recycling authorities can make informed decisions, optimize maintenance schedules, and improve the overall effectiveness of the recycling process.

4. User-Friendly Interface: Continuously refine the user interface to make it more intuitive and user-friendly. Clear instructions, visual indicators, and intuitive touchscreens can help users easily operate the machine and understand the recycling process. Additionally, incorporating multiple language options and accessibility features will ensure inclusivity and improve user experience.
5. Enhanced Energy Efficiency: While the current machine has low energy requirements, further efforts should be made to optimize energy efficiency. This can be achieved by utilizing energy-saving components, exploring alternative power sources such as solar panels or kinetic energy capture, and implementing smart power management systems that minimize energy consumption during idle periods.
6. Covering the Machine: The machine needs to be encapsulated preferably with sheet metal to ensure fixed light conditions for the sensor and also make the machine more presentable.
7. Robust and Durable Construction: Strengthen the machine's construction to enhance durability and longevity. Using high-quality materials, reinforced components, and protective coatings will extend the machine's lifespan, reduce

maintenance needs, and minimize the environmental impact associated with frequent replacements.

8. Expansion of Accepted Materials: Consider expanding the range of recyclable materials that the machine can handle. In addition to plastic bottles, future iterations could incorporate the capability to accept other commonly used recyclables such as aluminum cans, glass bottles, and paper products. This will broaden the machine's impact and encourage more comprehensive recycling practices.
9. Integration with Incentive Programs: Explore the possibility of integrating the machine with incentive programs to further incentivize recycling. By offering rewards or discounts to users who recycle, the machine can encourage increased participation and engagement, promoting a culture of sustainability.

By implementing these recommendations, future iterations of the Reverse Vending Machine can significantly enhance its functionality, usability, and environmental impact. Continuous improvement and innovation in this field will contribute to a more sustainable future by effectively reducing plastic waste and promoting recycling practices.

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