MAKERERE UNIVERSITY

COLLEGE OF ENGINEERING, DESIGN ART AND TECHNOLOGY
SCHOOL OF ENGINEERING
DEPARTMENT OF MECHANICAL ENGINEERING

Project Implementation Report

Design and Construction of an Automated Multipurpose Distiller

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A report submitted to the department of Mechanical Engineering in partial fulfillment of the requirements for the award of Bachelor of Science in Mechanical Engineering of Makerere University
September 2022

DECLARATION

I Kayemba Augustine hereby declare that the work which is being presented in this report was fully prepared by me and contains true information of the Project Execution Report for an Automated Multipurpose Distiller at the Mechanical Engineering Department of the College of Engineering, Design, Art and Technology in Makerere University – Kampala, in partial fulfillment of the requirement for the award of a Bachelor's Degree in Science in Mechanical Engineering.

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APPROVAL

This is to acknowledge that this project report was conducted under my supervision and guidance. It was submitted in partial fulfillment of the award of the Bachelor of science in Mechanical Engineering of Makerere University.

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ACKNOWLEDGEMENT

The learning experience throughout this project implementation was the great opportunity to study the topic of my choice in depth at a point when I was reaching the academic maturity. This developed not only my personal knowledge but the academic skills and knowledge as well.

I am grateful to the Mechanical Engineering Department of Makerere University - Kampala, without whom this work would not have been possible; Mr. Kisekka Gerald, who guided this project to completion with the utmost patience and kindness, Mr. Ndemere Joseph, who guided me and provided me with valuable feedback; Mr. Wabwire Andrew and Mr. Kasakye Phillip without whose tutelage this work would be impossible; my friends and work colleagues and *most importantly*, my wonderful *Parents* for their encouragement and *unconditional support*.

ABSTRACT

Steam distillation is the widely used method for the extraction of essential oil for many years. These essential oils are used in foods, medicines, cosmetics, perfumes etc. It can be a money earning business for the community. Industrial distillation products such as essential oils, ethanol and methanol are very crucial raw materials for the pharmaceutical industry and utilities for hospitals. The current industrial distillation technologies are specialized to a single distillation product and moreover very expensive to startup and entail high maintenance costs yet the counterpart small scale distillation technologies are very energy-inefficient and manual and thus have the lowest distillate product yield rates. Herein is discoursed a robust integrated versatile medium-duty distillation solution technology that is automated to satisfactorily meet the consumers' needs ranging from optimized high distillate concentration yields, to optimized high energy-efficiency to flexibility with the nature of distillation process raw material. Since the water essential oil distillation is notorious for its inflexibility with herbage raw material as well as its very low energy efficiency while the industrial dry steam also demands very high running-energy and start-up costs with, the water-steam essential oil distiller was considered with a modified closed heater-temperature control loop so as to do away with its only drawback of deterioration of raw material and thus decreased product yield as compared to the dry steam essential oil distiller. Such a distillation technology would have to be multipurpose so as to enable the local distillation businesses operate smoothly through both seasonally markets of ethanol and essential oils

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1. INTRODUCTION

Industrial use of essential oils

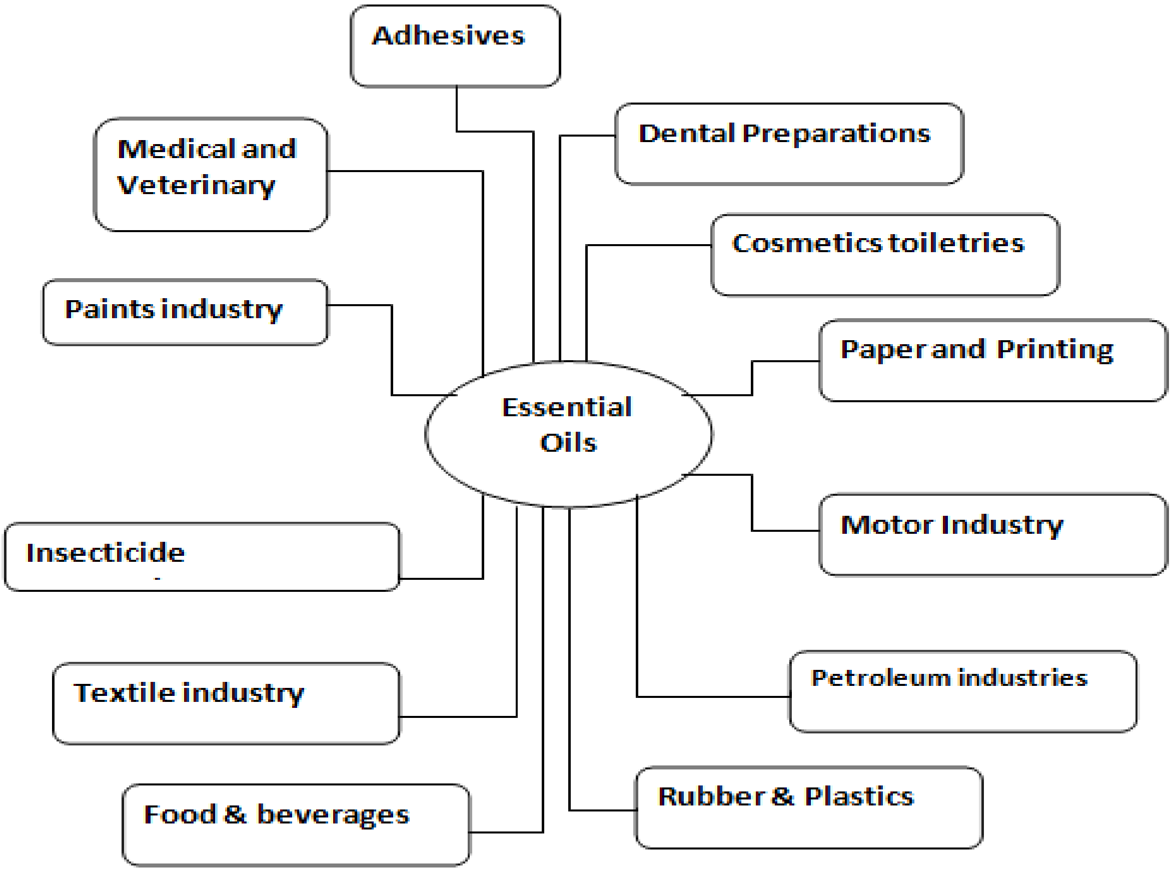


Figure 1: Industrial uses of essential oils

As seen in the figure above, essential oils are very are diversely important to the Ugandan economy for their many applications and thus their production majorly attracted attention for improvement which inspired this project as discoursed herein

1.2. BACKGROUND

Essential oils have gained much importance nowadays. These oil compounds are derived from plant materials. The oil produced contains the essence or flavor of plant materials. Major essential oil distillation technologies include Steam distillation, Hydro-diffusion, Hydrolysis, Cohobating, extraction by expression, Pr-Latrice process, Sub-matrices process, hot maceration process, micro-distillation and Protoplast technique among others (Ali Talati, 2017). As for as the extraction of most tropical herbs' essential oils is concerned, literature shows that researchers have opted to use steam distillation method for extraction of its essential oil (Aziz et al., 2018). Four (4) pieces of equipment are needed for this whole essential oil distillation process which includes the still, a steam fractionation column, condenser and a liquid-liquid separator. The designing process of all the four pieces of equipment as well as their mechanical design is discoursed herein with all the parameter calculations in detail. The cost analysis enables at understanding the economics of the engineering design, and the recommendation to strategically minimize the construction costs with the improved distiller design. The safety control, health, and environmental factors are also worthy a consideration to give the full insight into the process with every aspect. Because of product design economy reasons, the ethanol distillation process is to run *sequentially* with the essential oil distillation process, one at a time other than parallelly. This enables both distillation processes to utilise common machine resources thus greatly reducing the production costs of the distiller as specialised parts are eliminated. However, this calls for a dynamic control system that enables the precise distillation of both ethanol and essential oils on the same hardware, which is definitely, automation.

The extraction of essential oils by steam distillation requires a process that commonly uses large, centralized pieces of equipment such as boilers, stills, condensers and separators. Such pieces of equipment require a high initial purchase which is unaffordable by most Small and Median Enterprise farmers and even groups of farmers in most developing countries such as Uganda. Furthermore, some essential oils come from very delicate flowers that must be pre-processed before the essential oil distillation process. Thus, for functional and economic reasons, there is evidently a demand for small-scale, decentralized and energy-efficient steam distilling technology.

Some researchers such as Jessica Ferguson managed to separate alcohol from a water/alcohol mixture at 77.9^{0}C to a peak purity of 95.4% but however, employed manual and thus laborious distillers (Sirromet Wines Pty Ltd (Au), 2015); whereas other research organisations such as Niir Project Consultancy Services (India) also managed to distillate a wide range of essential oils using microwave essential oil distillation process which implies that the quality of the essential oil product was degraded and that their distillation method was unsaclable (Niir Project Consultancy Services (India), 2018). Such gaps left by the aforementioned researchers motivated this study as detailed in the *Literature review* section

1.3. PROBLEM STATEMENT

The current small scale steam distillation technologies are very energy-inefficient, laborious, have very high startup costs and are moreover specialized to specific distillation processes of specific raw materials and thus cannot serve the seasonal fluctuating markets of especially both ethanol and essential oil demands due to their inflexible distiller hardware.

1.4. OBJECTIVES

1.4.1 MAIN OBJECTIVE

To design and construct a cost-effective multipurpose automated distiller technology of essential oils and ethanol, which can be replicated in ordinary Ugandan workshops using locally available materials.

1.4.2. SPECIFIC OBJECTIVES

- To determine the design requirements
- To develop conceptual and detailed designs of a less laborious distiller
- To design hardware controller software for optimal energy-efficiency distillation
- To construct and test the prototype

1.5. SCOPE

The solution technology presented herein only focuses on the design, analysis, validation and construction of the optimal automation and *hybridization* of existent locally constructed essential oil and batch ethanol distillation technologies. This study the optimal design of both hardware and hardware controller software for an automated distillation process as well as the construction of the *feasibility incremental* prototype of the multipurpose distiller as discoursed herein.

1.6. JUSTIFICATION

The inflexibility of the current small scale steam distillation technologies with the nature of the distillation process called for a distillation technology that allows the sequential on-board resource-sharing of both essential oil distillation and ethanol distillation hardware for the various distillation processes so that the construction costs for the feasibility incremental prototype are reduced due to the sequential sharing of hardware resources. Furthermore, the seasonal fluctuation of the demand of ethanol and essential oils to the local Small and Medium Enterprises (SMEs) called for a flexible distillation technology so that they are kept in business in any distillation market season booms.

Because the current small scale steam distillation technologies are very energy-inefficient, laborious and have very high startup costs, it was thus necessary to design, construct and test the feasibility incremental prototype of an affordable automated energy-inefficient distillation technology.

2. LITERATURE REVIEW AND GAPS

2.1. ESSENTIAL OIL DISTILLATION

The main advantage of distillation is that it can generally be carried out with some very simple equipment, close to the location of plant production. Even in relatively remote locations, large quantities of material can be processed in a relatively short time. Distillation is less labor intensive and has a lower labor skill requirement than other extraction methods.
Steam distillation is the most advanced type of distillation, as the name suggests, steam distillation is the process of distilling plant material with steam generated outside of the still in a satellite steam generator generally referred to as a boiler. An obvious drawback to steam distillation is the much higher capital expenditure needed to build such a facility, as shown in the figure below.

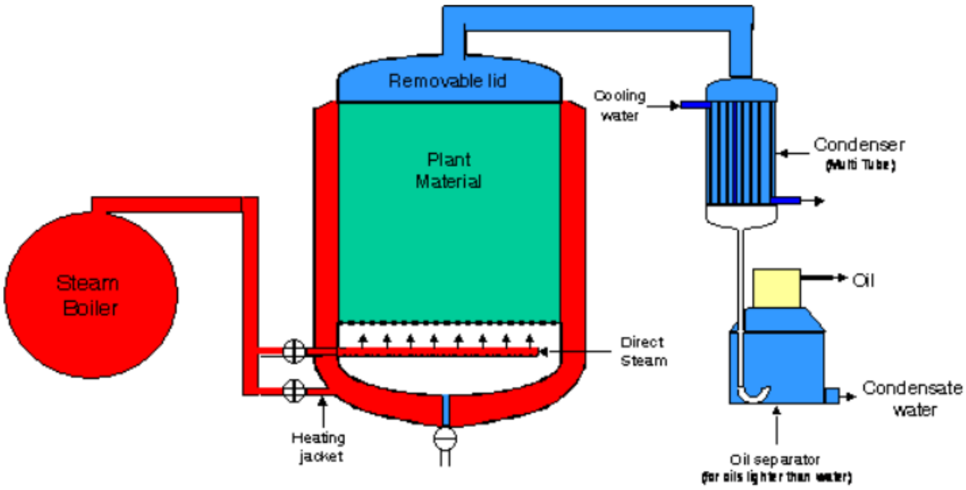


Figure 2: The concept of steam distillation

Niir Project Consultancy Services (India), a research organisation achieved the distillation of a wide range of essential oils such as rose oil extraction, chilli oil, ginger oil, black pepper oil, chilli oleoresin, cresols, menthol oil, clove oil and citronella oil, patchouli oil and garlic oil using microwave –primed essential oil distiller distillation process which gave lower quality essential oils and was definitely was unsaclable (Niir Project Consultancy Services (India), 2018)

2.2. ETHANOL DISTILLATION

There are two general types of distillation processes that appear applicable to farm-size fuel alcohol production with present technology. One is the continuous-feed distillation column system, in which a beer containing constant alcohol content is continuously pumped into a column. The other is a pot-type distillation system, in which a batch of beer, with the heavy solids (spent grain) not removed, is simply boiled in place to vaporize the alcohol. The alcohol-water vapors are then forced to flow through a distillation column to bring about concentration. These two processes are discussed in detail in the following pages. There are other fractional distillation systems that may or may not use a column as we normally think of such units. They include centrifugal techniques, mechanical rotating wipers in a tube, etc., and are not discussed here.
Presently, only few industries produce bio-ethanol fuel largely because of the cost of importing a sophisticated distiller. Therefore introducing an affordable distiller enables the engagement of more industries into the bio-ethanol production as well as encourage local producers to produce bio-ethanol for fuel rather than consumption which has a negative national economic

effect. It was therefore imperative to develop an ethanol distiller that can produce high quality bio-ethanol at locally affordable low costs which can be achieved by appropriately tuning and optimizing the thermal efficiency, distiller capacity, bio-ethanol yield, distillation rate, distillation productivity and distillation efficiency of the ethanol distiller.

2.3. AUTOMATED DISTILLATION

In the pharmaceutical industry, automated distillation which is a combination process between extraction and distillation process, is widely carried out to separate waste solvent mixture of acetone-methanol because of minimum-boiling azeotrope properties of acetone-methanol mixture. In the operation, water has been used as solvent. Automated distillation has been proposed to improve purity of the distillate. The solvent always has been charged into the still until it gives the purity of desired product. The automated distillation operates at total reflux ratio and controlled the reboiler holdup which must not exceed the maximum capacity at any time within the entire operation period to avoid column flooding. Mathematic models can be used to represent processes' dynamic behavior according to the experimental results obtained in a previous work. Relevant studies have showed that the process behavior of automated distillation is highly nonlinear. Consequently, this project proposes automated distillation to handle the versatile nonlinear process dynamic behavior. In addition, the optimization is necessary for an optimal solvent feed rate profile of automated distillation achieving the desired purification of acetone. This can also be obtained using neural network based optimization strategy. The process controller models and the user input referential temperature values are the factors affecting purification of desired product (K. Jariyaboon1, 2011).

2.4. GAPS IN EARLIER RESEARCH AND TECHNOLOGICAL DEVELOPMENTS

2.4.1. LIQUID-LIQUID SEPARATOR

Oils separate from water according to their density because they are immiscible or only sparingly soluble. If their density is less than 1.00, then they will float and are called “lighter than water” oils, whereas if their density is greater than 1.00, then they will sink and are referred to as “heavier than water” oils, therefore, currently different oil separators have to be used for the two types of oils as shown in the figure below.

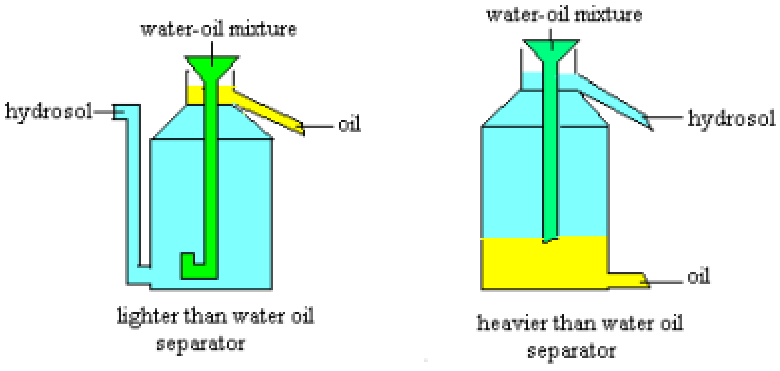


Figure 3: The existent two types of liquid-liquid separators

Thus, it important as stated in the specific objectives to design a multipurpose *oil-water separator* technology compatible to the broad range of essential oil densities

2.4.2. POSSIBLE MEASURES FOR TECHNICAL IMPROVEMENTS

There are some improvements that could result in enhancement of the distillate yield and optimize the operating conditions for example,

- Temperature sensitivity analysis should be carried out to see the effect on yield of oil.
- Results of varying solid to water ratio should be examined.
- Effect of distillation time on yield of the extracted oil should be investigated.

2.4.3. DISTILLATION PROCESS CONTROLLERS

The old fashioned open loop distillation controllers are the obvious reason for the horrible energy inefficiency chiefly due to the unmonitored nature of the process. Such process controllers popularly take the form of a human being controlling the distiller. Artificial Intelligence (AI) controllers, in particular the Machine Learning (ML) controllers such as Artificial Neural Network (ANN) controllers are popularly used to control nonlinear processes such as the versatile distillation process which would have instead required much complex analytical process controllers that which need intensive computational resources.

Neural network model is like human newborn where it needs to be developed, trained and taught to perform desired tasks. Its can capture the (highly nonlinear process) relationship between the inputs and the outputs of the true process with a considerably lower computational load than required by a mathematic model of the plant, learn easily and require little or no a priori knowledge of the structure. Neural networks have been applied in the neural network based modeling, optimization and system processes control (K. Jariyaboon1, 2011). However, because the student did not possess the competence of modeling and deploying the amazing Artificial Neural Network (ANN) controllers to the distiller's computational hardware, the rather conventional Proportional Integral Differential (PID) controllers were considered for implementation of the project as detailed in the *System processes controls design* section.

3. METHODOLOGY

The automated multipurpose distiller allows the raw material in the still to be heated by onboard electric means or auxiliary burning flame heater means. The vapor mixture from the still is then concentrated by appropriate distillation column techniques and finally condensed in the condenser by a portable onboard condensation technique that needs no external coolant water supply. The process actuators such as electric heaters are servo-thermally controlled by a central microcontroller feed with feedback process data signals from sensors such as temperature sensors. The microcontroller is controlled by custom process hardware controller software.

The identified problems from the consumer needs data that were collected from Prof BIORESEARCH Company Limited were grouped under the specific objectives and matched with solutions methods of the constructed distiller technology so as to ensure the coverage of the consumer needs. The table 1 below shows the objectives-methods mapping

3.1. DETERMINING THE DESIGN SPECIFICATIONS

Product design specifications were benchmarked from the existent median-scale distillers whereas consumer needs data were collected through interviews with technical personnel at Prof Bioresearch Company Limited (Ug) who are lead users of distiller technologies; the collected data were analysed to identify the critical user needs which were later used to set the target design specifications of the feasibility incremental prototype as discoursed herein.

3.1.1. LITERATURE REVIEW AND BENCHMARKING

Various similar distillers on the market were researched for distillers' performance and configuration data such as the steady distillation rate, the still batch capacity and … among others; which were influential in the generation of the product design requirements, the product specifications as well as the distiller's conceptual design as discoursed in detail in the *Preliminary design* section.

Operation and Optimization of a batch extractive distillation process has been studied only few literatures. One literature has proposed the operation under constant reflux ratio and optimization of quantity and quality product in a fixed time with the smaller quantity of solvent. S.M. Milani has presented the operation in the batch mode and optimized the solvent feed rate for maximum recovery of high purity top product in an automated distillation process. The optimization of the maximum product problem and the minimum time problem are considered by one and two time intervals for each distillation task (to separate products) in both a batch mode and a semi-continuous mode (K. Jariyaboon1, 2011). This thus motivated the automation of the multipurpose distiller design concept so as to achieve optimal energy efficiency as discoursed in detail in the *Systems processes controls design* section

3.1.2. CONSUMER NEEDS DATA COLLECTION

The consumer challenges data that were collected from PROF BIORESEARCH Company Limited which is a lead user of essential oil distiller technologies were a remarkable inspiration to the design and construction of the Automated Multipurpose distiller technology and include,

- Stills are fond of exploding
- Counterfeit condenser tubes
- Too hot distillates which make the essential oil to evaporate off easily
- Low and unpredictable distillate yields
- Inability to determine if discarded herbage are fully exhausted of essential oils
- Difficulty to adding water to the still during distillation
- Inability to predict real-time boiler water level
- Leaking steam from the stills
- Fluctuating energy sources, that is, from firewood to charcoal

- Strict technical care is needed during the distillation, which is sometimes boring

3.2. DEVELOPING OF CONCEPTUAL AND DETAILED DESIGNS OF A LESS LABORIOUS DISTILLER

The Axiomatic Design Theory (ADT) was used as the generic method for the design, analysis, and assessment of the distiller's hardware. To make system complexity manageable at each iteration, the Axiomatic Design Theory (ADT) was adopted so as to narrow down a set of Functional Requirements (FRs), Design Solutions (DSs), and Performance Metrics (PMs) that are most critical to given applications, and the rest of FRs, DSs, and PMs were formulated as design constraints based on available manufacturing assets and current system states as summarized in the figure below.

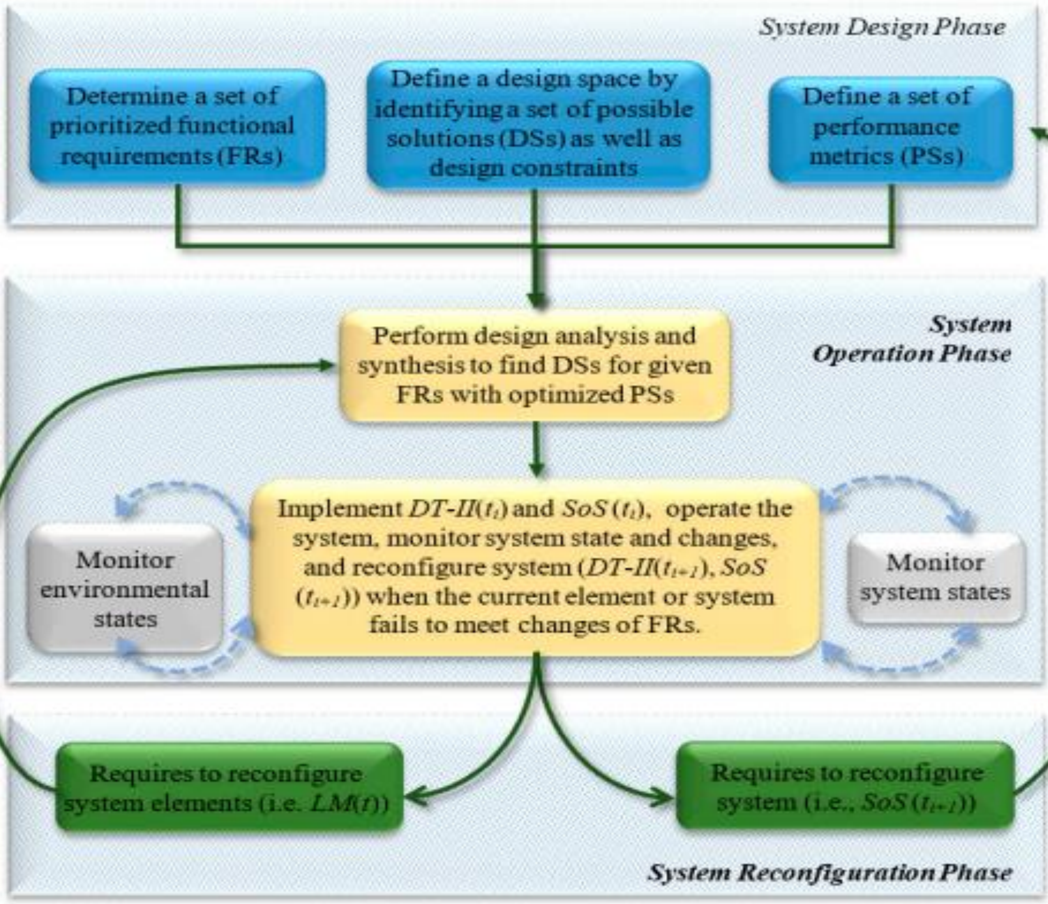


Figure 4: The Axiomatic Design Theory (ADT)

Deliverables and consumables

The automated multipurpose distiller is versatile at producing concentrated distillates of essential oils, azeotropic methanol and azeotropic ethanol depending on the raw materials loaded in the still with amazing energy efficiency. In its routine running, the automated multipurpose distiller requires heat energy from various energy sources in particular, both electrical heat sources such as powered electrical heating elements as well as direct flame heat energy sources such as burning charcoal, briquettes, natural gas, biogas and firewood. The distiller equipment can also sequentially consume raw materials for both the essential oils and ethanol; that is the herbage or tree barks and the fermented brew respectively.

3.2.1. FUNCTIONAL REQUIREMENTS (FRS)

According to performance and configuration data of other distillers on the market, the design functional requirements for the successful implementation of the constructed distillation technology were researched and documented as detailed in the *Target Product specifications* section

3.2.2. MULTI-OBJECTIVE OPTIMIZATIONS (MOO)

Performance metrics can however conflict with each other. Jiang et al. (Jiang, Ong, Zhang, & Feng, 2014) discussed the contradictions of system design metrics in Multi-Objective Optimisation (MOO). The case of the design of the machine control program computational hardware where various optional computational hardware devices were optimally selected basing on their cost price, total number of General-purpose Input / Output Pins (GIOP) pins and the size of the Synchronous Dynamic memory (SD-RAM) by use of a three dimensional (3D) graph was considered here for the demonstration of the application of the Multi-Objective Optimisation (MOO). The summary of trade-offs for the machine hardware control program computational hardware is also shown in the graph below

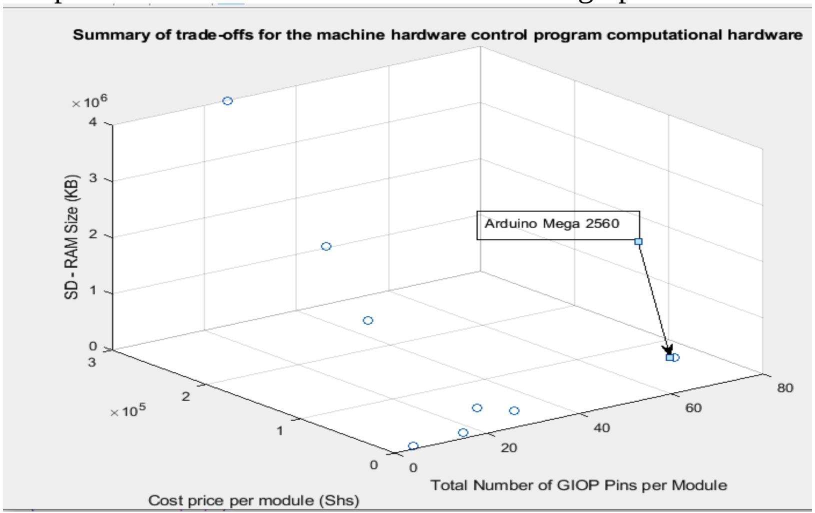


Figure 5: Summary of trade-offs for the machine hardware control program computational hardware

3.2.3. DESIGN SOLUTIONS (DSS)

This in a nutshell includes the design of major machine end-effectors of the distillate collection system. The machine components' mass reduction and material optimisation was analytically performed with the use of Computer Aided Design tools such as AutoDesk Inventor Nastran and MATLAB so as to achieve the most economical design of the automated multipurpose distiller components' which was crucial to reduction of the project expenses as discoursed in detail in the *Detailed design* section.

The Product Design and Development procedures were employed to develop and screen the incremental prototype as discoursed in chapter 4 (Product design). The configuration of the mechanical part of the automated multipurpose distiller was greatly influenced by the analytical machine design procedure where the various key machine design parameters were analytically estimated by use of the appropriate forward propagation analytical estimator functions as discoursed in detail in the *Detailed design* section

3.3. DESIGNING THE HARDWARE CONTROLLER SOFTWARE FOR OPTIMAL ENERGY-EFFICIENCY DISTILLATION

Hardware controller software were designed by use of tools such as the Program flowcharts to translate the functional specifications to visual algorithms, Pseudo –code were used to translate the program flow charts to human-readable program algorithms and the Integrated Developer Environments (IDEs) such as MATLAB/SIMULINK and the Arduino IDE were used to translate and write the human-readable program algorithms into computer-readable programs as well as deploying the hardware programs onto the prototype's computational hardware as detailed in the *Processes controller software design* section.

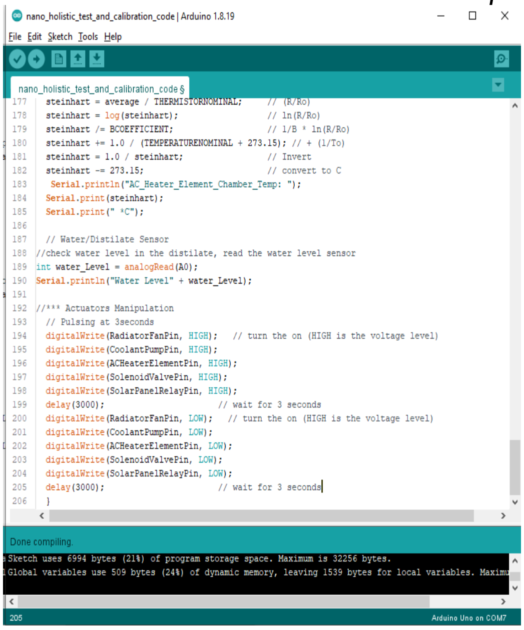
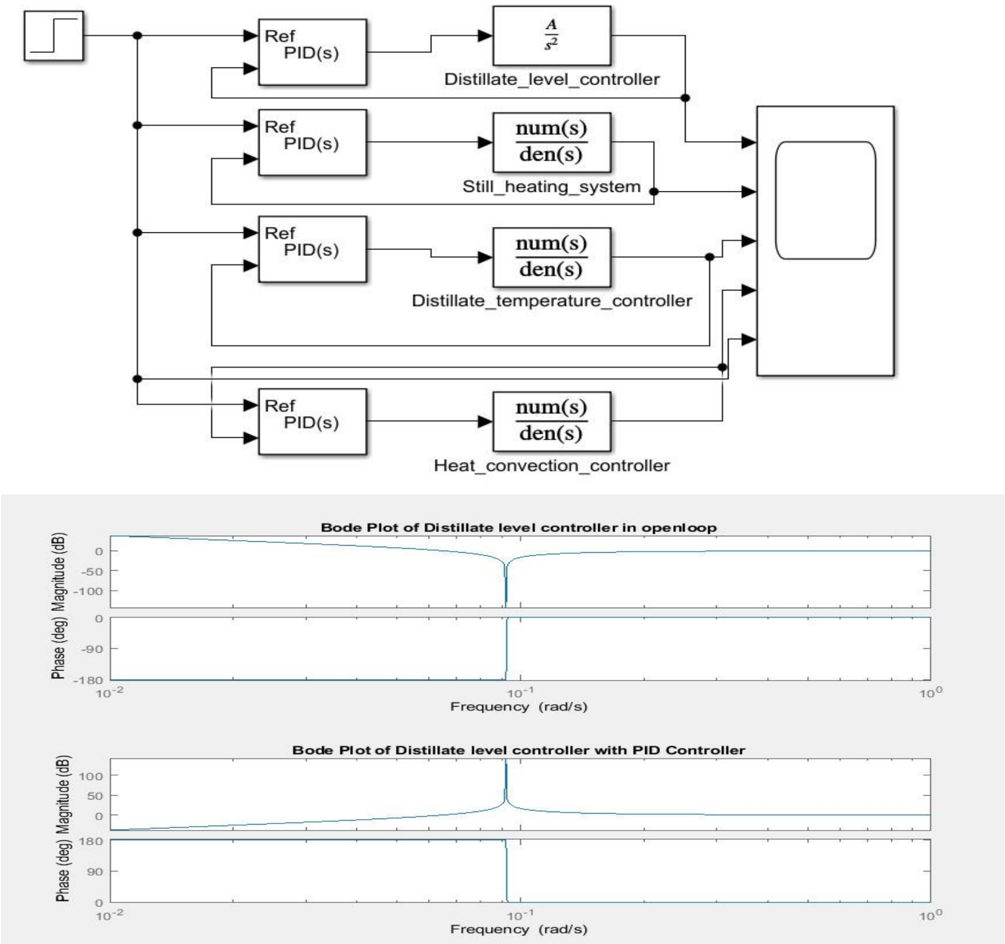


Figure 6: A typical hardware programming session using the Arduino Integrated Developer Environment (IDE)

The figure above shows a typical process of translating and writing the human-readable program algorithms of the sensors' handler function into computer-readable programs and later deploying the hardware program onto the prototype's computational hardware. The achievements of the hardware controller software design process were the holistic hardware controller software which is a MATLAB/SIMULNK model shown in *Appendix H*

The distiller's hardware controller software was developed modularly where modules of the holistic hardware control program was developed from Program Flowcharts through corresponding pseudo-code and algorithms and finally translated to a MATLAB/SIMULINK program for hardware deployment. MATLAB was considered in preference to the Compiler (C) language for the Arduino Integrated Developer's Environment (IDE) since it eased the design and deployment of sophisticated process controllers such as Proportional Integral Differential (PID) controllers and Artificial Neural Networks (ANNs) controllers among others.



(A)

(B)

Figure 7: Validation of the optimal design of the process controllers using MATLAB/SIMULINK (A): The Processes PID controllers under optimal configuration (B): A typical Bode diagram analysis during the validation of the process controllers' configurations

The figure above illustrates how state of the art control systems design tools such as MATLAB/SIMULINK were used to optimally configure and validate the process controllers of the prototype

3.2.4. PERFORMANCE METRICS (PMS)

The table below shows a summary of the desirable performance configuration of the multipurpose distiller

Part	Parameter	Designed Value	Marginal Value
Still	Threshold still volume	200Ltrs	226Ltrs
Condenser	Distillate Temperature	30^0C	27^0C
Heater primer	Distillate yield loss	1g/s	1.1g/s
Process controller	Maximum controller loop overshoot error	10%	5%
Process vessel	Energy efficiency rate per distillate volume	7.2kJ/Ltr	6kJ/Ltr

Table 1: Desirable system performance metrics

The table below shows the software tools that were used to deploy the Axiomatic Design Theory for designing the multipurpose distiller

Software

Proteus Pro
Arduino IDE
Solid Edge
Altair Inspire
MATLAB/SIMULINK

Table 2: Software tools used to deploy the Axiomatic Design Theory method

3.4. CONSTRUCTION AND TESTING OF THE FEASIBILITY INCREMENTAL PROTOTYPE

The designed feasibility incremental prototype was mainly constructed by fabrication means such as welding by use of various tools and equipment as listed in the tables below whereas the testing varied from virtual hardware controller software test, through manual actuator tests, automated sensors' tests and to holistic field tests of the prototype.
The table below shows the list of the equipment used at the Mechanical Workshop throughout the construction process of the multipurpose distiller

	Equipment
Pillar drill	Flat file
Pillar grinder	Pliers
Lathe machine	Bench vice
Welding inverter	Hack saw
Welding shield	Ball pen hammer
Hand drill	Anvil
Angle grinder	Claw hammer
Centre drill	Scriber
Centre punch	Tape measure
Vanier calipers	Chuck and chuck key
1/2foot Steel ruler	Digital multi-meter
Iron solder	

Table 3: Equipment used in the implementation of the construction and testing of the incremental prototype

Consumable	Quantity
6mm diameter Drill bits	2pieces
Metal saw	1piece
12mmX12mm Turning tool	1piece
E6013 Welding electrodes	1packet
Soldering wire	8metres

Table 4: Consumables used for the implementation of the construction and testing of the incremental prototype

3.5. LIMITATIONS

It is obvious that there are several factors that compromise the *full* validity of some of the assumptions and justification of the thesis of the need for the design and construction of an Automated Multipurpose Distiller for low income-earning countries such as Uganda. Such factors include,

- The inadequacy in public information domain of several plant material properties such as density, moisture content and specific heat capacity of the plant herbage raw materials
- Since the essential oil and bio-ethanol distillation industries are still under-developed in Uganda, it is very challenging to get firsthand experimental data, which are crucial for the design of the distillation technology.

- Open source references are not available due to commercializing of most key and technical information resources as proprietary intellectual properties. Although resources are available on some websites, their full technological background is not given due to intellectual property protection measures such as copy right.

4 PRODUCT DESIGN

The automated multipurpose distiller prototype presented herein consists of an ethanol distiller operating sequentially with an essential oil distiller. In the essential oil distiller, steam is produced in the boiler and then it is directed to the column where plant herbage raw material is placed. Towards the end two phases are collected an organic phase (essential oil) and other aqueous phase, the hydrosol (M. Khaijeh, 2008).

4.1 CONCEPTUAL DESIGN

This includes the development of the design product specifications, the generation of the feasible functional concepts as well as the selection of the most suitable functional concepts as detailed below

4.1.1. TARGET PRODUCT SPECIFICATIONS

From the performance and configuration data of other distillers on the market, as well as the consumer needs data which were used to obtain the design requirements, the design functional requirements for the successful implementation of the constructed distillation technology were researched and documented as discoursed below.

- The distillate yield loss due to overheated condensers must be minimised to less than 1%
- *Robust* condensation of the distillate must be achieved to a temperature of 30^0C
- The multipurpose distiller must cost less than the current imported distillers, Shs.3,500,000/=
- The optimal *robust* process controllers must achieve still temperature overshoots less than 10%
- Energy-source-versatile hybrid distillation technology must compatible to at least three (3) distinct heat sources
- The multipurpose *oil-water separator* technology compatible to essential oil densities ranging from 200kg/m^3 to 2,100 kg/m^3
- The high proof ethanol distillation capability must achieve a minimum 90% proof

The performance specifications of the distiller prototype are summarised in the table below

Specification	Designed value	Marginal value
Distillate production rate	1.000g/s	1.111g/s
The distillate yield loss due to overheated condensers	< 1%	< 0.8%
Maximum distillate temperature	40^0C	35^0C
Cost price of the distiller	Shs.3,500,000/=	Shs.3,200,000/=
Maximum still temperature overshoot	10%	8%
Proof of ethanol distillation	90%	93%
Separable essential oil density in the oil-water separator	300kg/m^3 - 2,000 kg/m^3	200kg/m^3 - 2,100 kg/m^3

Table 5: Product design specifications

4.1.2 CONCEPT GENERATION

This section discourses the selection and design of the mode of actuation of the actuators and the end-effectors as by the Axiomatic design theory (ADT)

I. The still's thermal primer mechanism

The still's thermal primer mechanism is responsible for appropriately duly heat the liquid system in the still so as to raise the temperature in the still as well as the temperature in the fractionating column to desired values as per the user's input. The thermal end-effector is the still whose shape was chosen as cylindrical due to its relatively high strength-to-weight ratio while the material used for demonstration purpose was mild steel due to its relatively low cost price; stainless steel was not used due to its highest cost price that would have made the project's implementation impossible had not it been abandoned. The thermal priming mechanisms that were considered include;

- The dry flame heater mechanism.

  The dry flame heater mechanism would use a dry burning flame from burning heat sources such as briquettes and firewood to thermally prime the still and its contents as shown in the figure below. This mechanism however, was not considered for implementation as it needed extra time to calibrate the machine hardware processes control program so as to incorporate it; the time which was not enough.

Table 6: The dry flame heater mechanism

- The Direct Current (DC) heater element mechanism

  The Direct Current (DC) heater element mechanism would use an electrically powered Direct Current (DC) heater element to thermally prime the still and its contents as shown in the figure below. This mechanism however, was too expensive for consideration for implementation as it needed a high power Alternating Current (AC) rectifier which would even lower the power carrying capacity of the electric powertrain.
- The Alternating Current (AC) heater element mechanism

  The Direct Current (AC) heater element mechanism uses an electrically powered Alternating Current (AC) heater element to thermally prime the still and its contents as shown in the figure below. This mechanism was chosen for implementation since it required no high power Alternating Current (AC) rectifier as compared to the the Direct Current (DC) heater element mechanism; which would have even lower the power carrying capacity of the electric powertrain.

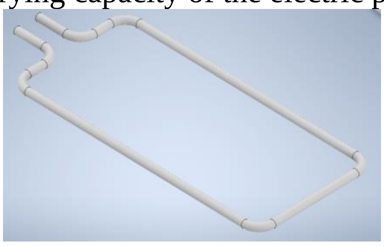


Figure 4: Figure 8: The Alternating Current (AC) heater element mechanism

II. Robust condenser mechanism

This robust condenser mechanism is needed for condensing the pressurised steam from the still to a distillate of a preset temperature as per the user input. This includes thermal actuators and thermal linkages such as the condenser tube, heat radiator and the coolant; as well as actuators such as the coolant pump and the radiator fans. The material that was considered for the condenser tube was copper due to its highest thermal diffusity and thus highest heat conduction efficiency while water was considered as the coolant due to its cheap affordability in terms of cost price as well as its high specific heat capacity and thus a high specific thermal capacitance which effectively eliminated thermal overshoots in the robust condenser system. The robust condenser mechanisms that were considered here include,

- The helical tube condenser mechanism
  This used a helical copper tube that was fully immersed in a coolant-filled enclosure of the condenser; the copper tube condenses the distillate by conducting its heat energy to the coolant which is in turn cooled in the radiator as shown in the figure below. The helical tube condenser mechanism was chosen for the implementation of the project due to the ease of fabrication of the helical tube as compared to that of the parallel tubes

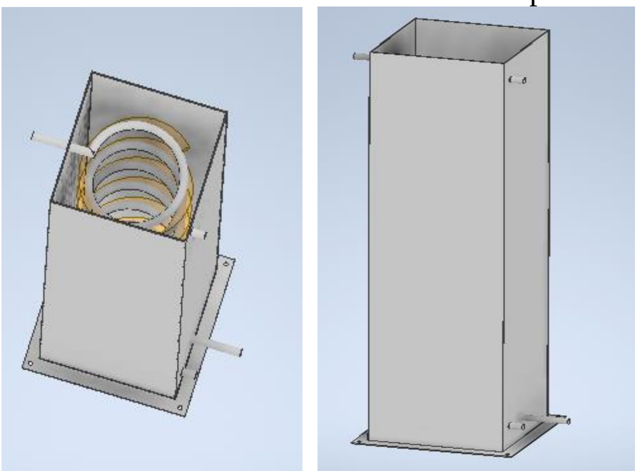


Figure 9: The helical tube condenser mechanism

- The parallel tubes condenser mechanism
  Here, parallelly connected copper or stainless steel tubes that are fully immersed in the coolant-filled enclosure of the condenser are used; the parallel tubes condense the distillate by conducting its heat energy to the coolant which is in turn cooled in the radiator as shown in the figure below. The parallel tubes condenser mechanism was not considered for the implementation of the project due to the difficulty of fabrication of its fabrication as compared to that of the helical tube condenser.

4.1.3 CONCEPT SELECTION

4.1.3.1. STEAM DISTILLATION CONCEPT SELECTION

There are a variety of technologies that can be used for essential oil extraction as shown in the table below

Metric	Cost	Product quality	Ease of implementation
Distillation concept	Score	Score	Score
Hydro-distillation	Low	4	4
Solvent extraction	High	3	3
Supercritical fluid extraction	Very high	2	1
Ultrasound and microwave assisted processes	Very high	1	2
Water distillation	Very low	5	4

Table 7: Trade-offs for the selection of the essential oil distillation technology concept

The key feature of water distillation is that it extracts the essential oil at a temperature below the boiling point of essential oil compounds which have boiling temperatures of around 200^0C.

Water distillation eliminates the risk decomposition of oil components by reducing the operating temperatures below their boiling points.

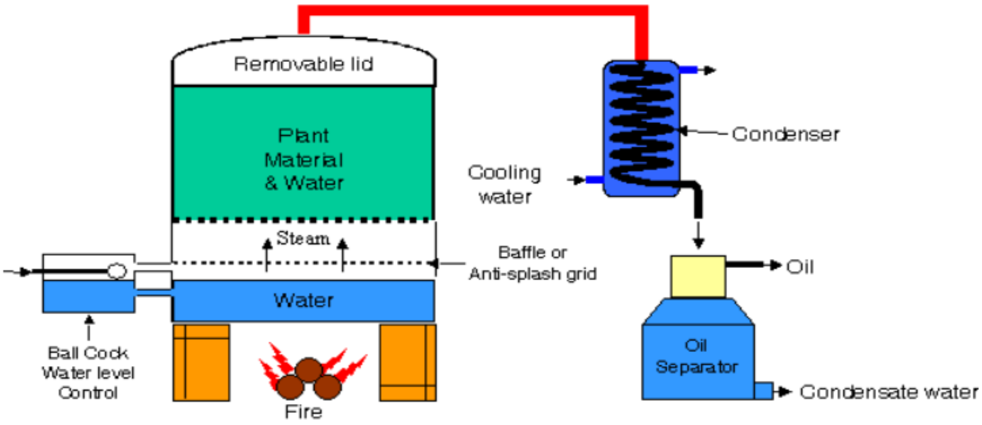


Figure 10:Water-steam distillation method

Furthermore, Steam and water distillation is a faster process than water distillation so it is more energy efficient and was thus chosen to be optimized by automation for the essential oil distillation.

4.1.3.2 SELECTION OF HARDWARE CONTROL PROGRAM COMPUTATIONAL RESOURCES

The hardware control program architecture was highly determined by the cost of the hardware control program computing hardware, that is whether a microcomputer, a microcontroller or both. Such computing hardware considered include,

I. The microcontroller

This was the cheapest electronic computing hardware option in terms of cost price despite that it called for improvisational challenges in some caes. The available microcomputers can be programmed using either MATLAB or the open source Arduino Integrated Developer's Environment (IDE) thus the Compiler (C/C++) languages had to be used in writing the hardware control program as translated from its algorithms. By identity of the technologies, unlike the microcomputer which has its inbuilt onboard Operating System software and thus allows sophisticated multitasking and multithreading, the microcontroller only has its Kernel software thus cannot directly, support seamless real-time multitasking and multithreading. This was the main drawback of using microcontrollers as the hardware control program computing hardware. Examples of microcontrollers considered include,

i. The Arduino Nano board

It required only one Arduino Nano board connected in parallel with the Arduino Uno board which possesses the Liquid Crystal Display (LCD) keypad and input shield for the implementation of the project's electronic computing hardware as shown in the figure below.

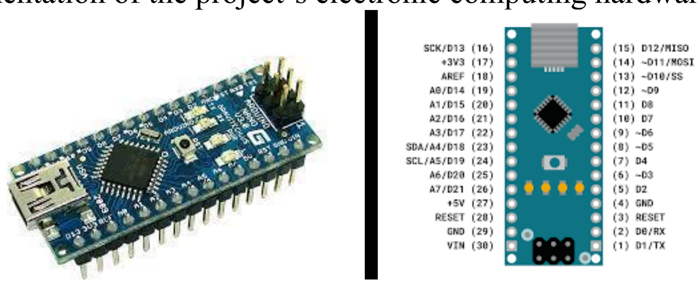


Figure 11: Arduino Nano (Left): Microcontroller, (Right): Pin layout

ii. The Arduino Uno board

This is much like the Arduino Nano except that it is much worse than the Arduino Nano at almost every score metric considered as illustrated in the figure below. Because of possesses the Liquid Crystal Display (LCD) keypad and input shield, it was most suitable to work in parallel with the Arduino Nano board for the implementation of the project's electronic computing hardware.

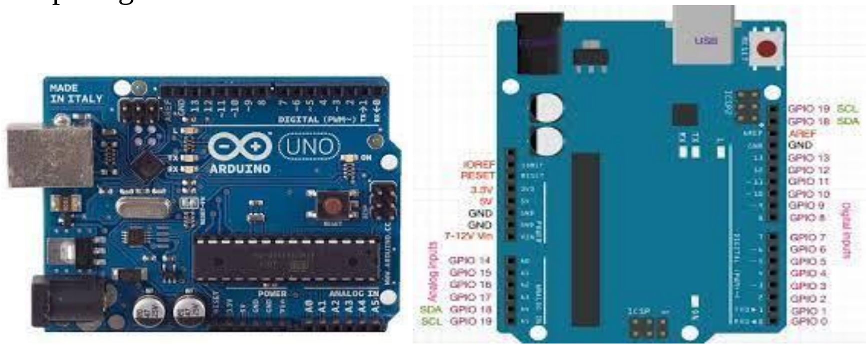


Figure 12: Arduino Uno (Left): Microcontroller, (Right): Schematic of pin layout

iii. The Arduino Mega2560 board

As shown in the figure below, this would have been the best Arduino microcontroller option since it has 76, 8KB of SDRAM and an onboard 16MHz clock I/O pins; had not it been of its cost ineffective incompatibility with the Liquid Crystal Display (LCD) keypad and input shield and was thus not considered for implementation of the project's electronic computing hardware.

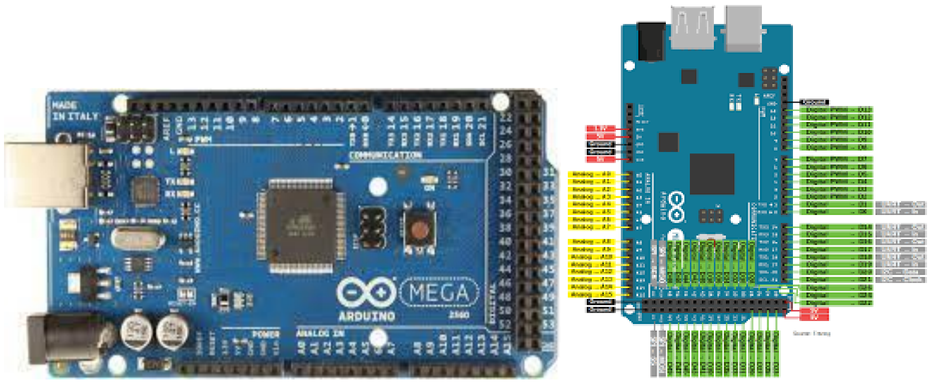


Figure 13:Arduino Mega (Left): Microcontroller, (Right): Schematic of pin layout

4.2 EMBODIMENT DESIGN

4.2.1 PRODUCT ARCHITECTURE

4.2.1.1PRODUCT FUNCTIONAL DECOMPOSITION

It consists of four main hardware equipment units. The first unit is the still, where oil extraction is done. The second unit is the fractionation column where the vapor composition of the essential oil is improved series of repetitive evaporation and condensation sequences. The third unit is the condenser where, vapors are condensed, fourth and last unit is the liquid-liquid separator which separates the essential oil from the hydrosol as shown in the figure below.

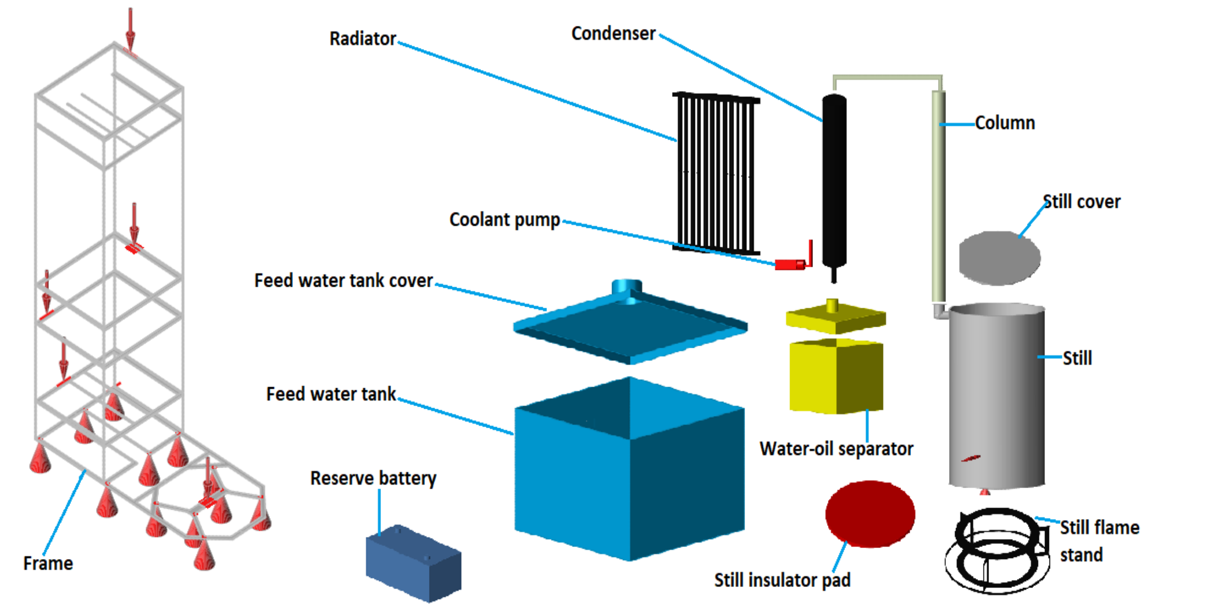


Figure 14: The Multipurpose Distillation functional decomposition diagram

The isometric and side views of the architecture of the technical assembly geometric model of the prototype is shown in the figure below

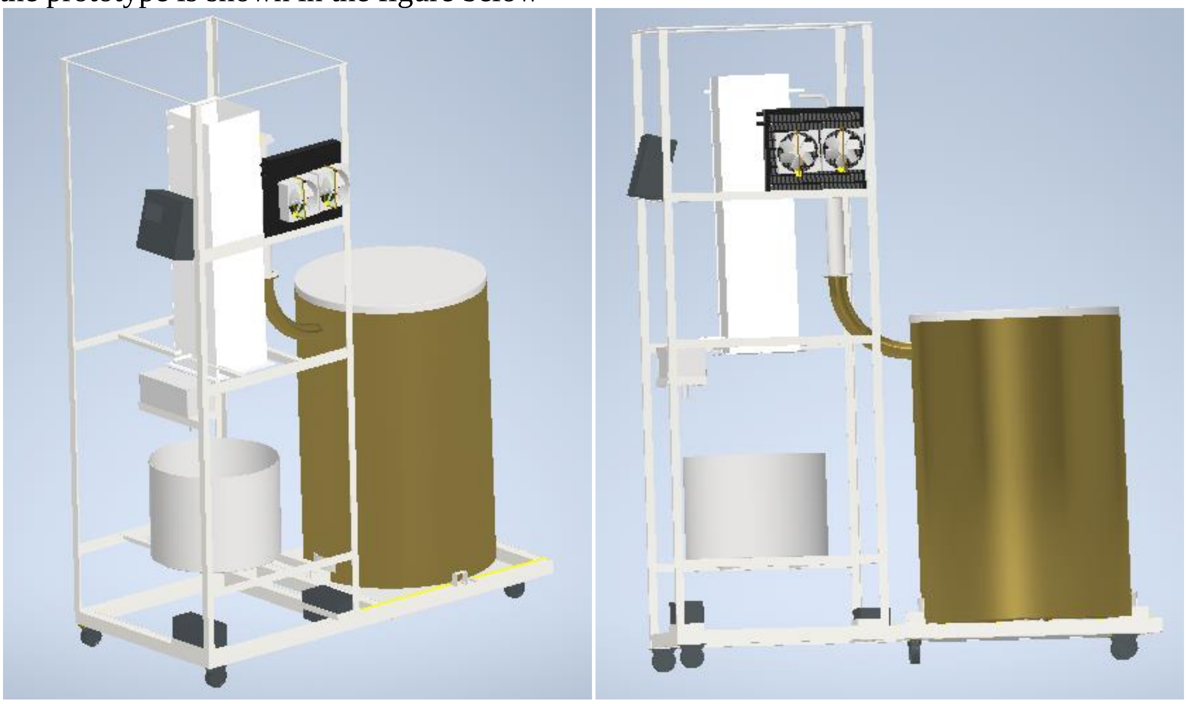


Figure 15: The technical model of the product design; (Left): Isometric view, (Right): Right

4.2.2. CONFIGURATION DESIGN

The configuration definition parameters of the automated multipurpose distiller were analytically computed as summarized in the table below and detailed in *Appendix C*

System Parameter	Shreshold Design Value	Lower Value	Upper Value	SI Unit	Remark
H_C_pump	4.1315	2.06575	6.19725	m	Pressure Head of coolant pump
P_C_pump	20	10.00000	30.00000	W	Power of coolant pump
P_still	0.1067	0.05333	0.16000	kW	Steady Heat into the

					still
D_b_pipe	0.0088	0.00438	0.00219	M	Diameter of fractionator column
Rad_LMTD	0.9941	0.49707	0.24853	K	LMTD of Radiator
1/U_rad	0.0040	0.00200	0.00100	W/m^2C	1/U of Radiator
A_rad	1.3318	0.66590	0.33295	m^2	Effective Radiator Area
L_cu_rad	28.25051	14.12526	7.06263		Length of Copper tube Radiator

Table 8: Configuration design

4.2.3 PARAMETRIC DESIGN

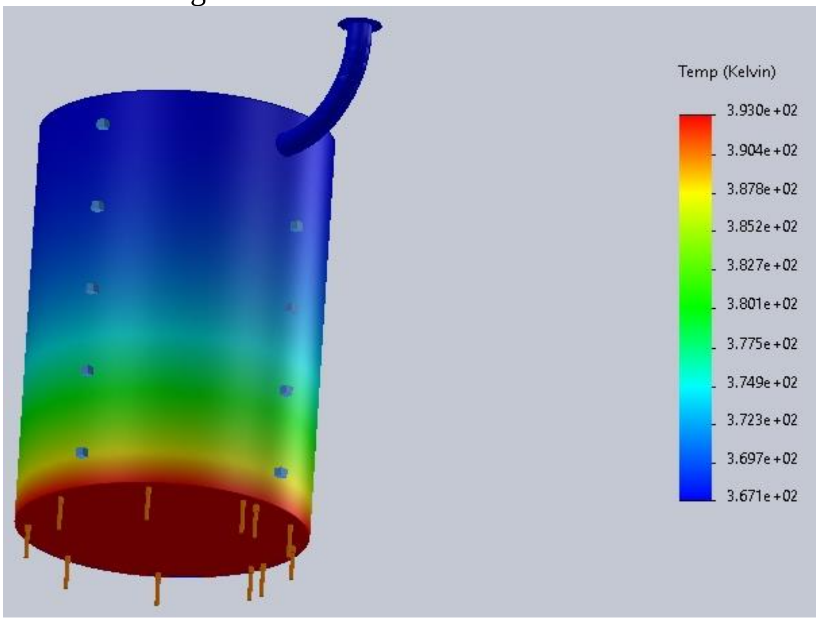
4.2.3.1. STILL DESIGN

For ethanol distillation, the boiler *still* shell was made of a stainless steel vessel for chemical inertness to the ethanol, and is cylindrical and oriented vertically as from the decision matrix below. The height of the boiler is moderate for quick even heat distribution in the entire content. When the amount of steam necessary to displace the oil, and the oil content is known, then the size of the boiler should be able to be determined. The detailed analytical design of the still is discoursed in Appendix A

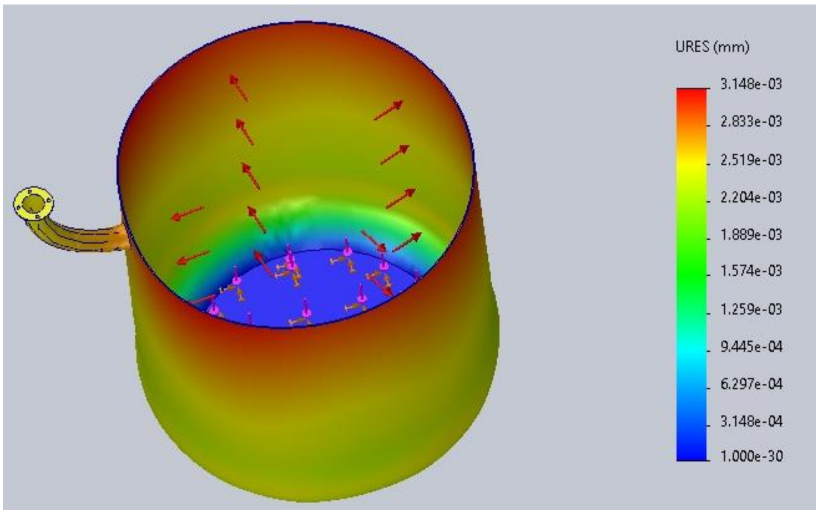
Metric	Cost price	Chemical Inertness	Ease of fabrication
Material	Score	Score	Score
Copper	3	2	4
Stainless steel	4	4	1
Galvanized steel	1	1	3
Brass	2	3	2

Table 9: Trade-offs for the selection of the still material

The geometric Computer Aided Design (CAD) model of the solution to the design of the still is shown in the figure below



(A)



(B)

Figure 16: Finite Element Analysis of the still A: Thermal analysis, B: Displacement analysis

4.2.3.2. ESSENTIAL OIL FRACTIONATION COLUMN DESIGN

A distillation column separates the mixture into its component parts, or fractions such as steam, based on the differences in volatilities. Therefore, a *stainless steel* material for the fractionating column was chosen as shown below while the detailed analytical design of the fractionating column is discoursed in Appendix A

Metric	Cost price	Chemical Inertness	Ease of fabrication
Material	Score	Score	Score
Copper	3	2	4
Stainless steel	4	4	1
Galvanized steel	1	1	3
Brass	2	3	2

Table 10: Trade-offs for the selection of the fractionation column material

The geometric Computer Aided Design (CAD) model of the solution to the design of the fractionating column is shown in the figure below

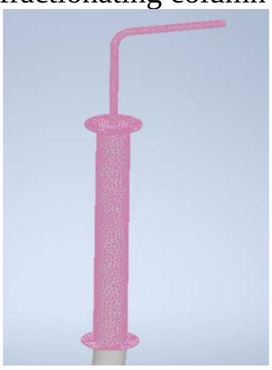


Figure 17: The geometric Computer Aided Design (CAD) model of the fractionating column

4.2.3.3.. CONDENSER DESIGN

Latent heat of condensation is involved as the phase change occurs inside and two phases exist. The target operational temperature was 303.15 K as according to the design requirements. The two main types of condensers are the multiple tube type or the coiled tube type. The coiled tubular condenser type was chosen over the multiple tube type as shown below, while the detailed analytical design of the condenser is discoursed in Appendix A

Metric	Coiled Tubular Condenser	Multiple Tube Condenser
Ease of fabrication	Easy	Difficult
Material	All metal types	Stainless Steel

Heat transfer	Poor heat transfer	Good Heat transfer
Pressure build-up during distillation	High	No
Need of reservoir	Needs large coolant reservoir	Needs fast running coolant

Table 11: Trade-offs for the selection of the condenser design

The geometric Computer Aided Design (CAD) model of the solution to the design of the condenser is shown in the figure below

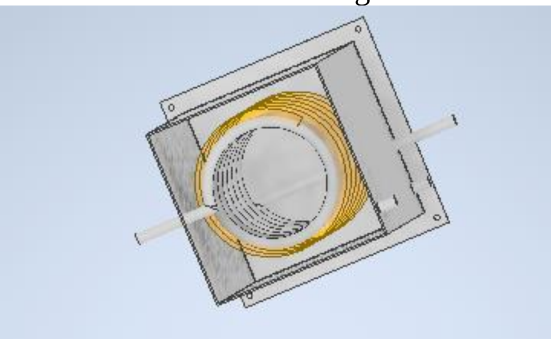


Figure 18: Top view of the geometric Computer Aided Design (CAD) model of the condenser

4.2.3.4. OIL-WATER SEPARATOR DESIGN

Essential oil decantation is a physical liquid-liquid separation process where the hydrosol water and the essential oil form separate immiscible phases and usually separated by density difference as shown in the figure below.

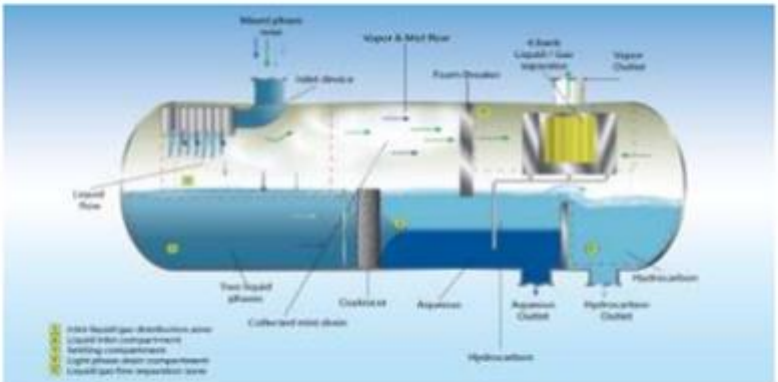


Figure 19: Oil-water separator

It is important that the oil separator should be large enough in volume to minimize turbulence because significant amounts of oil can be lost with the distillate water if the oil is not allowed to separate completely. It is recommended that the separator should be large enough to take the equivalent of more than 4 minutes of distillate flow without overflowing. Therefore, a stainless steel material for the oil-water separator was chosen as shown below while its detailed analytical design is discoursed in Appendix A

Metric	**Cost price**	**Chemical Inertness**	**Ease of fabrication**
Material	Score	Score	Score
Copper	3	2	4
Stainless steel	4	4	1
Galvanized steel	1	1	3
Brass	2	3	2

Table 12: Trade-offs for the selection of the oil-water separator material

The geometric Computer Aided Design (CAD) model of the solution to the design of the oil-water separator is shown in the figure below

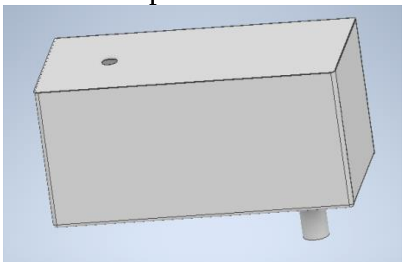
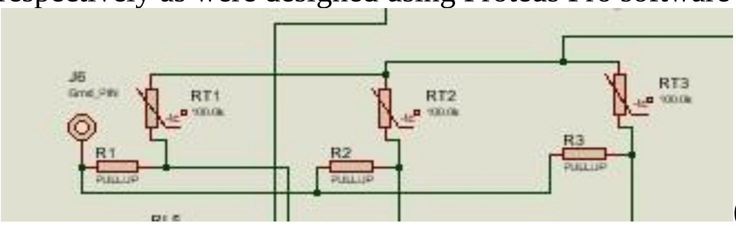


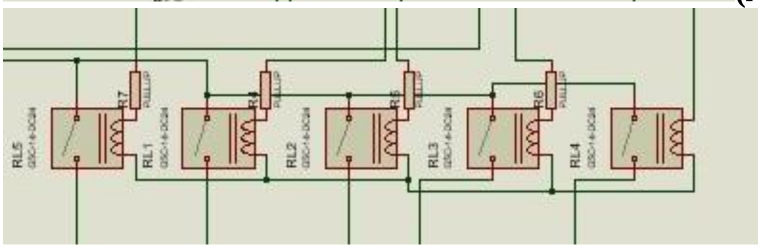
Figure 20: The geometric Computer Aided Design (CAD) model of the oil-water separator

4.2.3.5. SYSTEM PROCESSES CONTROLLER HARDWARE DESIGN

In this section, the design of the mechatronic hardware and other electric hardware for the multipurpose distiller are discoursed in detail. In a nutshell, this includes the design of major electronic components such as; the machines' hardware control program computational resources, electrical power tunnelling hardware, electric power supply hardware, mechatronic actuator hardware and the machines' hardware control signal routing hardware. The figure below shows the analogue sensors' circuit as well as the actuators' relay switch circuit respectively as were designed using Proteus Pro software



(A)



(B)

Figure 21: (A): Analogue sensors' circuit (B): Actuators' relay switch circuit

4.3 MATERIAL SELECTION.

This includes the design of the automated multipurpose distiller's frame structure as well as the selection of material of the machine's frame. Since the automated multipurpose distiller was reasonably an intensely-stress-loaded machine, the structural in its design process had to be performed first by analytical methods as discoursed in *Appendix C* and secondly validated by use of Computer Aided Design methods such the Finite Element Analysis as shown in the figure below.

4.3.1. CHOICE OF MATERIAL FOR THE FRAME

Mild steel was chosen as the machine's frame material as elaborated in the table below for the machine because;

- It was readily available on market.
- It could be easily and cheaply fabricated with the Mechanical workshop's MIG (Metal Inert Gas) welders into the machine frame.
- It was relatively cheapest in terms of the cost price from the point of purchase, through fabrication up to machining into the finished frame.

Material	**Relative cost of purchase**	**Relative cost of fabrication**	**Possibility of fabrication with the Workshop's equipment**

Mild steel	Cheap	Cheapest	Cheaply possible
Stainless steel	Most expensive	Expensive	Expensively possible
Plastic	Cheapest	Most expensive	Impossible
Aluminium	Expensive	Expensive	Expensively possible

Table 13: Trade-offs comparison of mild steel and other materials

4.4 SOFTWARE DESIGN

The machine control program was modularly designed as a combination of only five (5) functions that is, the Human-Machine Interface function, the Sensors Handler Function, the Processes Controller Function, the Gestures Handler Function and the Actuators Handler Function

4.4.1. THE HUMAN-MACHINE INTERFACE FUNCTION

This function parses user inputs to the Processes Controller Function and machine outputs to the output screen as illustrated by th program flowchart

Program pseudo-code

- On start, display the screen1 and initiate the machine run state to 0 (FALSE)
- While on screen1, if user presses the “right” key display screen2
- While on screen2, if user presses the “up/down” keys browse through the pre-defined still temperature values; if user presses the “select” key, capture the Referential Still Temperature value and display screen3
- While on screen3; if user presses the “up/down” keys browse through the pre-defined distillate temperature values; if user presses the “select” key, capture the Referential Distillate Temperature value and display screen4

Program flowchart

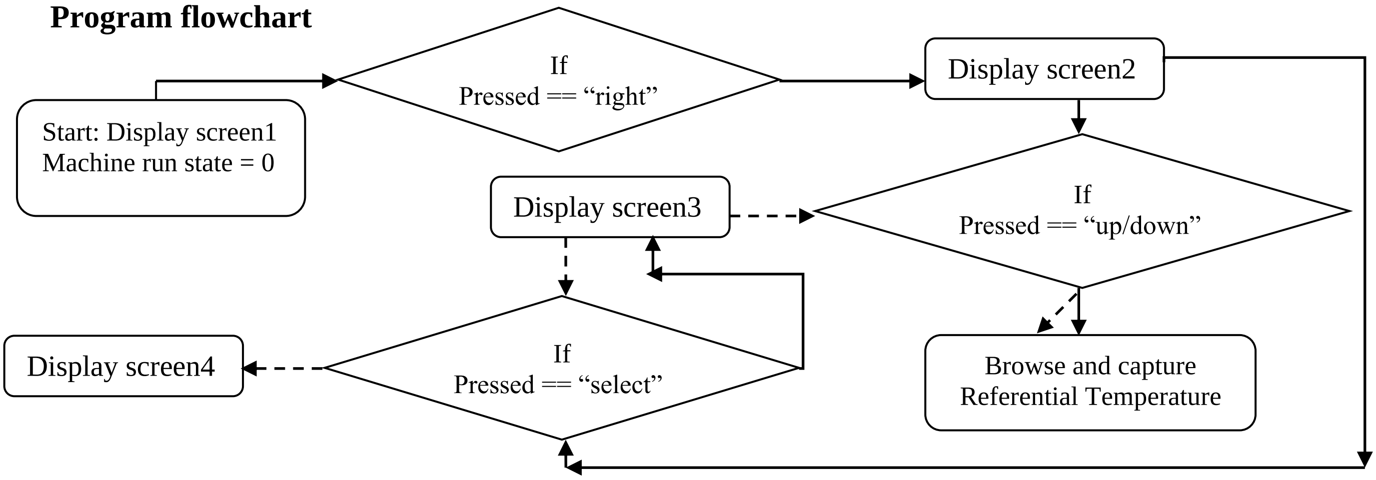


Figure 22: Program flowchart for the Human-Machine Interface function

MATLAB/SIMULINK program

The figure below shows the SIMULINK program model for the Human-Machine Interface function, the detailed user-defined MATLAB code for constituent functions are discoursed in *Appendix H*

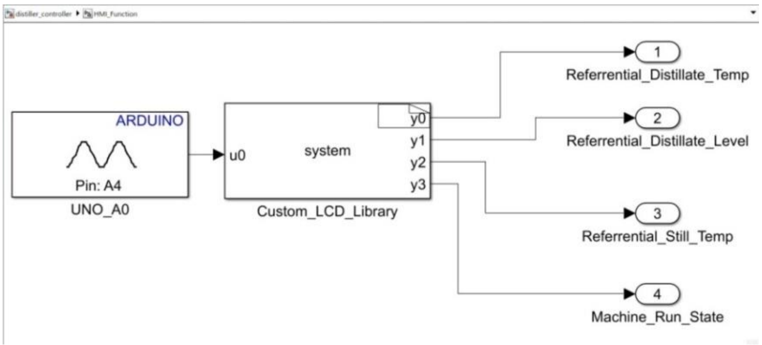


Figure 23: MATLAB/SIMULINK program for the Human-Machine Interface function

4.4.2. THE SENSORS HANDLER FUNCTION

This function Converts sensors' signals to numerical float data for the Sensors Handler Function as shown in the program flowchart

Program pseudo-code

- Capture the input analog signals from analog sensors, use the analog sensors function to generate appropriate float variables values for the Processes Controller Function
- Capture the input digital signals from digital sensors, use the digital sensors function to generate appropriate float variables values for the Processes Controller Function

Program flowchart

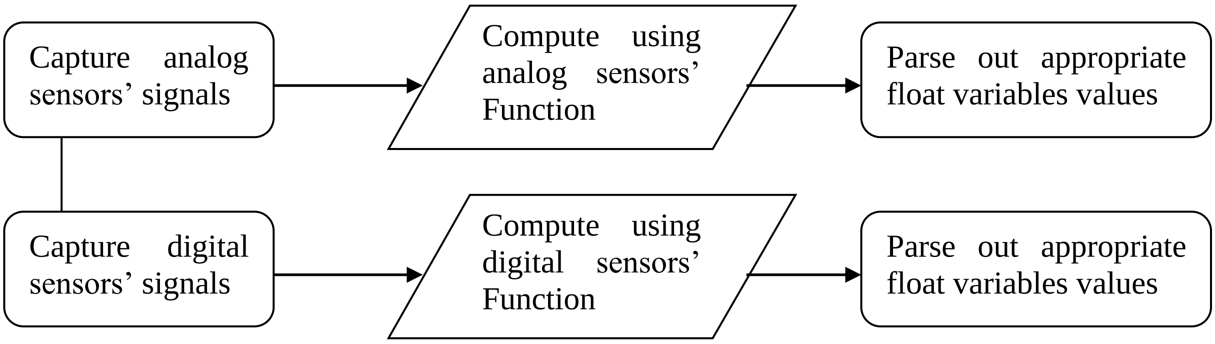


Figure 24: Program flowchart for the Sensors Handler Function

MATLAB/SIMULINK program

The figure below shows the SIMULINK program model for the Sensors Handler Function, the detailed user-defined MATLAB code for constituent functions are discoursed in *Appendix H*

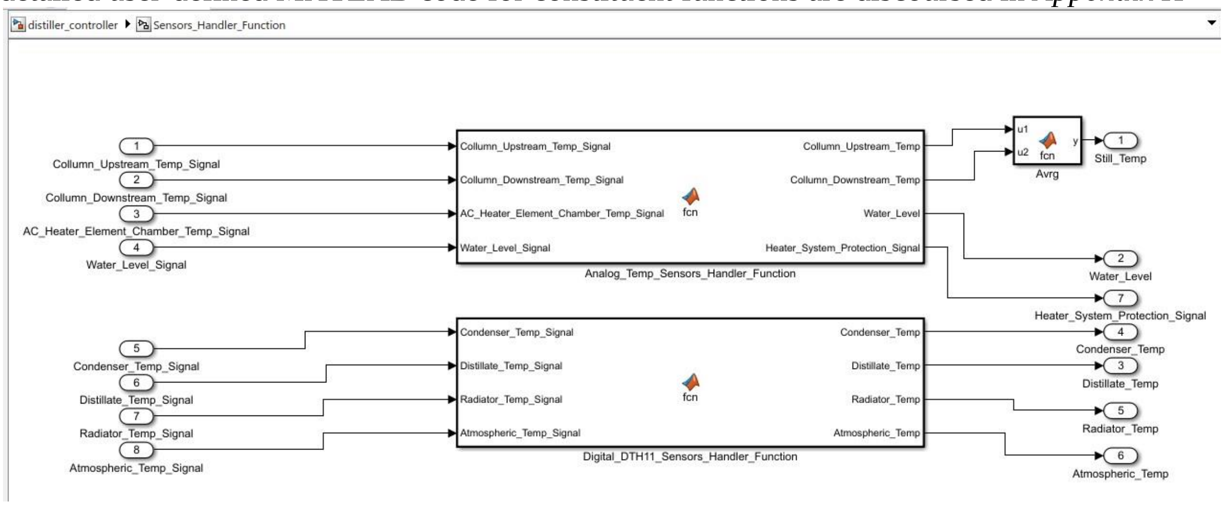


Figure 25: MATLAB/SIMULINK program for the Sensors Handler Function

4.4.3. THE PROCESSES CONTROLLER FUNCTION

This function uses sensors' data to appropriately control the actuators' switch states by use of the process controllers as actuation rules as illustrated by the program flowchart

Program pseudo-code

- Use the sensors numeric data to estimate the appropriate switch states of the actuators
- If the heater element's switch state changes generate a bleep signal and a red light signal for the ardon light
- If the temperature in the heater element exceeds 160^{0}C, set the heater system protection signal to "1"

Program flowchart

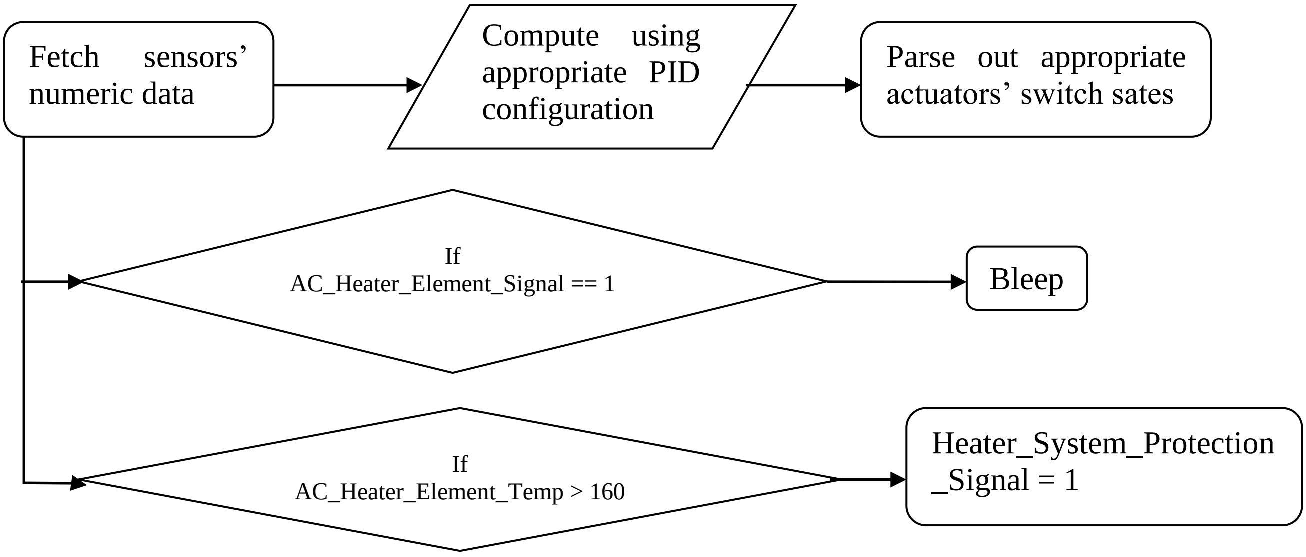


Figure 26: Program flowchart for the Processes Controller function

MATLAB/SIMULINK program

The figure below shows the SIMULINK program model for the Processes Controller function, the detailed user-defined MATLAB code for constituent functions are discoursed in Appendix H

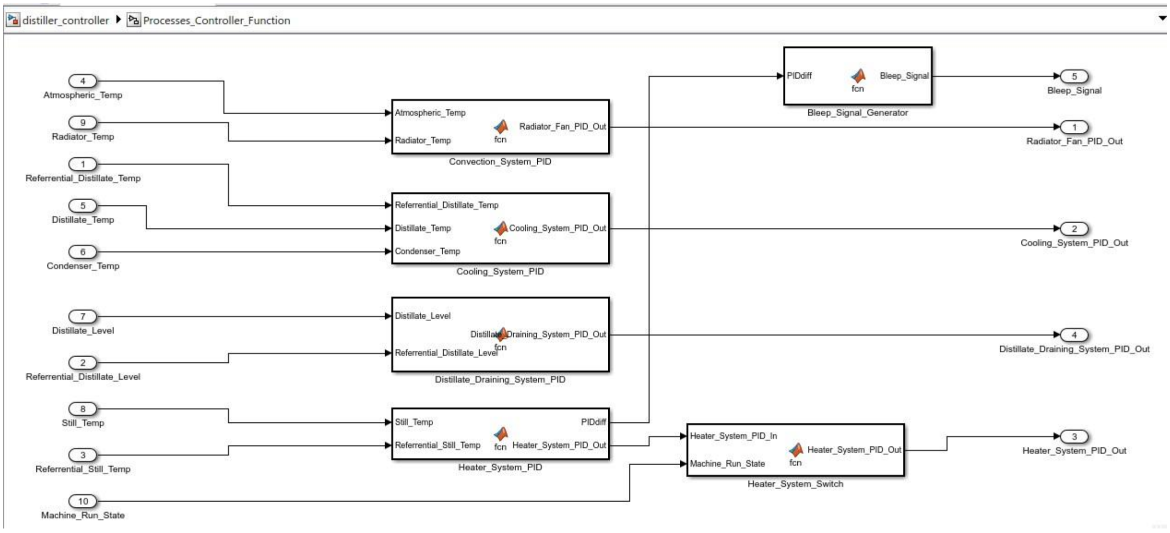


Figure 27: MATLAB/SIMULINK program for the Processes Controller function

4.4.4. THE GESTURES HANDLER FUNCTION

This function uses gesture outputs to alert o the user of the transient machine state that is, whether the machine is in “standby” or “run” or normally loaded or overloaded as shown in the program flowchart

Program pseudo-code

- Parse out the bleep signal to the bleep output pin
- Use the ardon light signals for “Green”, “Yellow” and “Red” to generate the appropriate RGB (Red-Green-Blue) output combinations for the ardon light

Program flowchart

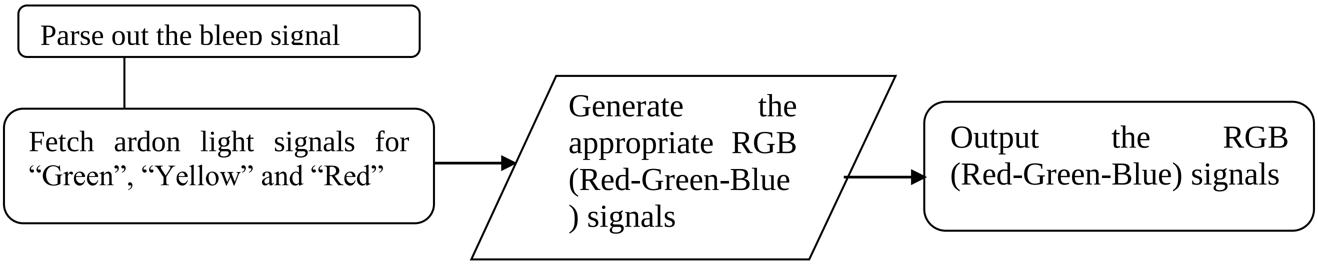


Figure 28: Program flowchart for the Gestures Handler function

MATLAB/SIMULINK program

The figure below shows the SIMULINK program model for the Gestures Handler function, the detailed user-defined MATLAB code for constituent functions are discoursed in Appendix H

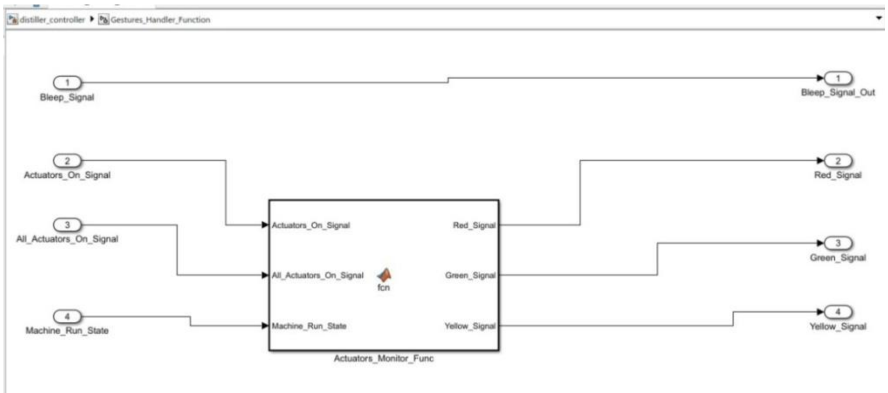


Figure 29: MATLAB/SIMULINK program for the Gestures Handler function

4.4.5. THE ACTUATORS HANDLER FUNCTION

This function uses signals from the Processes Controller Function to actuate the actuators accordingly as illustrated by the program flowchart

Program pseudo-code

- If an actuator’s switch state signal is “1”, write “HIGH” to the corresponding output pin, else write “LOW”
- Always invert the switch state for the heater element relay pin since it is a negative action relay switch
- If all actuators are on, set the “all actuators on” signal to “1”, else set the “all actuators on” signal to “0”
- If at least an actuator is on, set the “actuators on” signal to “1”, else set the “actuators on” signal to “0”

Program flowchart

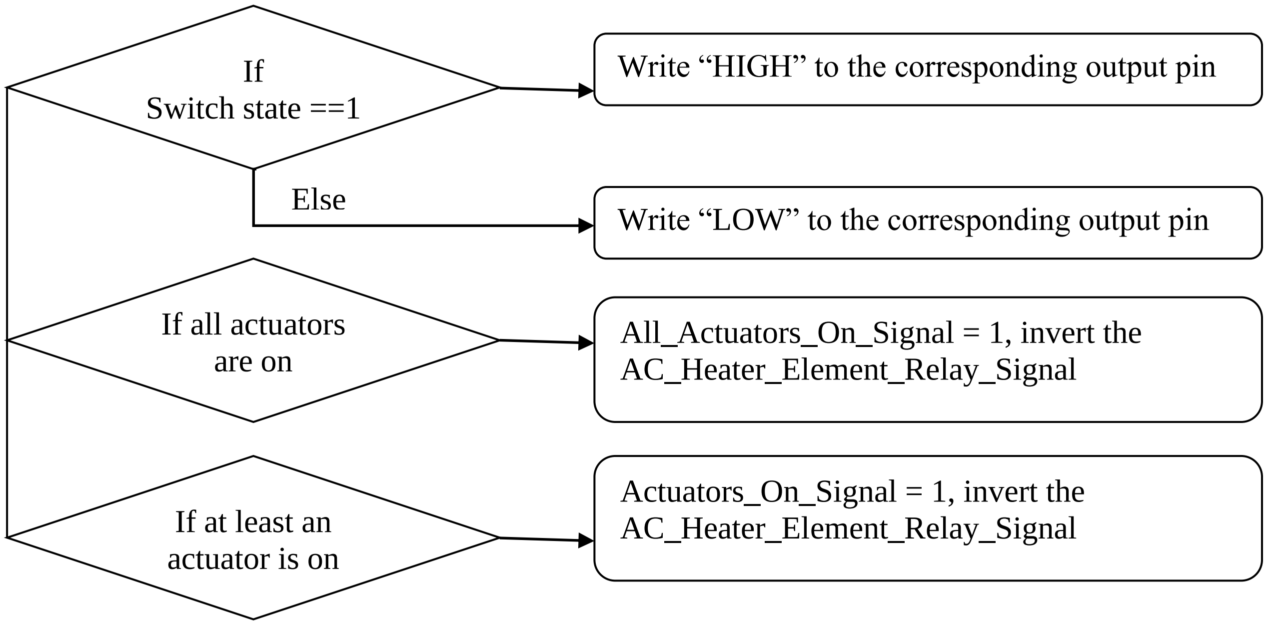


Figure 30: Program flowchart for the Actuators Handler Function

MATLAB/SIMULINK program

The figure below shows the SIMULINK program model for the Actuators Handler Function, the detailed user-defined MATLAB code for constituent functions are discoursed in Appendix H

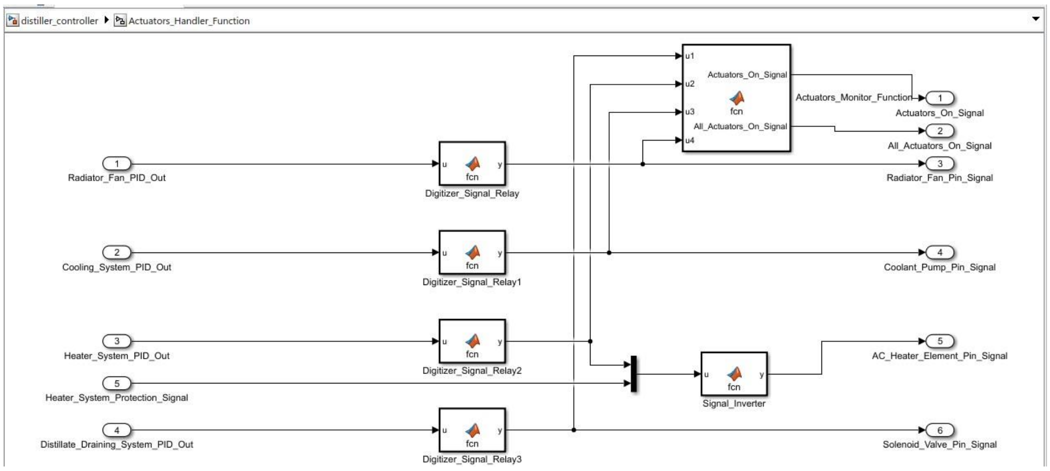


Figure 31: MATLAB/SIMULINK program for the Actuators Handler Function

4.4.6. SUMMARY OF THE SOFTWARE DESIGN PROCESS

The table below summarizes the process controllers design while the detailed holistic machine controller MATLAB/SIMULINK program is detailed in Appendix H

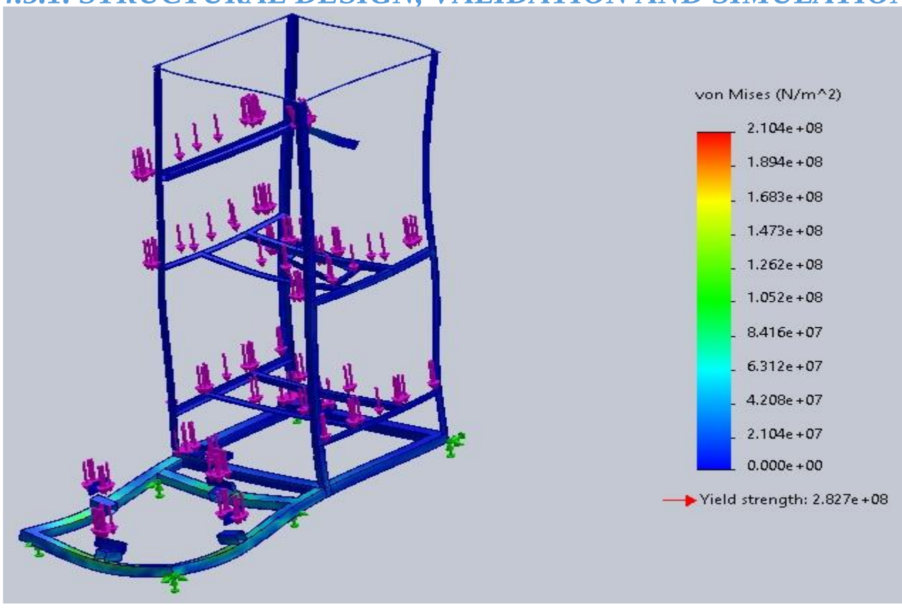
Function Index	Function name	Objective	Associated hardware
1	HMI_Function (Human-Machine Interface)	Parses users inputs to the Processes_Controller_Function and machine outputs to the output screen	Liquid Crystal Display (LCD) and keypad shield
2	Sensors_Handler_Function	Converts sensors’ signals to numerical float data for the	All sensors

3	Processes_Controller_Function	Processes_Controller_Function Uses sensors' data to control the actuators	--
4	Gestures_Handler_Function	Uses gesture outputs to alert o the user of the machine state	Bleep, ardon light
5	Actuators_Handler_Function	Uses signals from the Processes_Controller_Function to actuate the actuators accordingly	All actuators

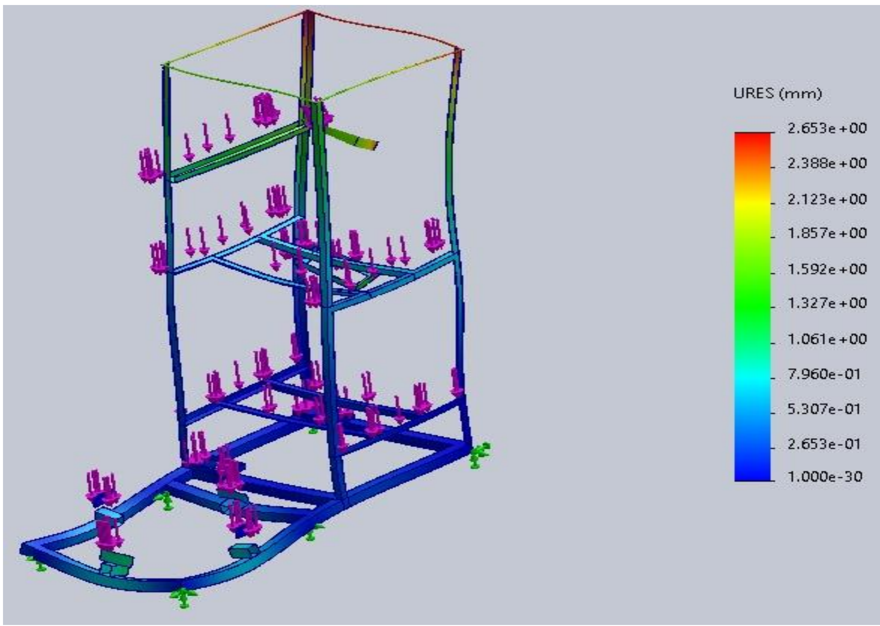
Figure 32: Summary of the Machine controller program design

4.5 DESIGN SIMULATION

4.5.1. STRUCTURAL DESIGN, VALIDATION AND SIMULATION



(A)



(B)

Figure 33: Structural Finite Element Analysis of the automated multipurpose distiller A: von Misses Stress analysis, B: Displacement analysis

As shown in the figure above, the frame was designed to have mounts for all on—board actuators whereas most sensors were instead glued onto the automated multipurpose distiller's frame. The structural analyses and validation for the feasible maximum stress as well as the maximum possible stiffness were performed with the use of AutoDesk Inventor Nastran as shown in the figure above. The detailed structural design of the automated multipurpose distiller is discoursed in Appendix E

4.5.2. PROCESSES CONTROLLERS DESIGN AND SIMULATION

Proportional Integral Differential (PID) process controllers were used to control the four (4) major onboard processes' actuators by residing the main microcontroller while depending on the user input referential temperature values as well as the real-time sensors' temperature readings as detailed in the MATLAB/SIMULINK Proportional Integral Differential (PID) controlled transfer function models of the onboard processes in the figure below

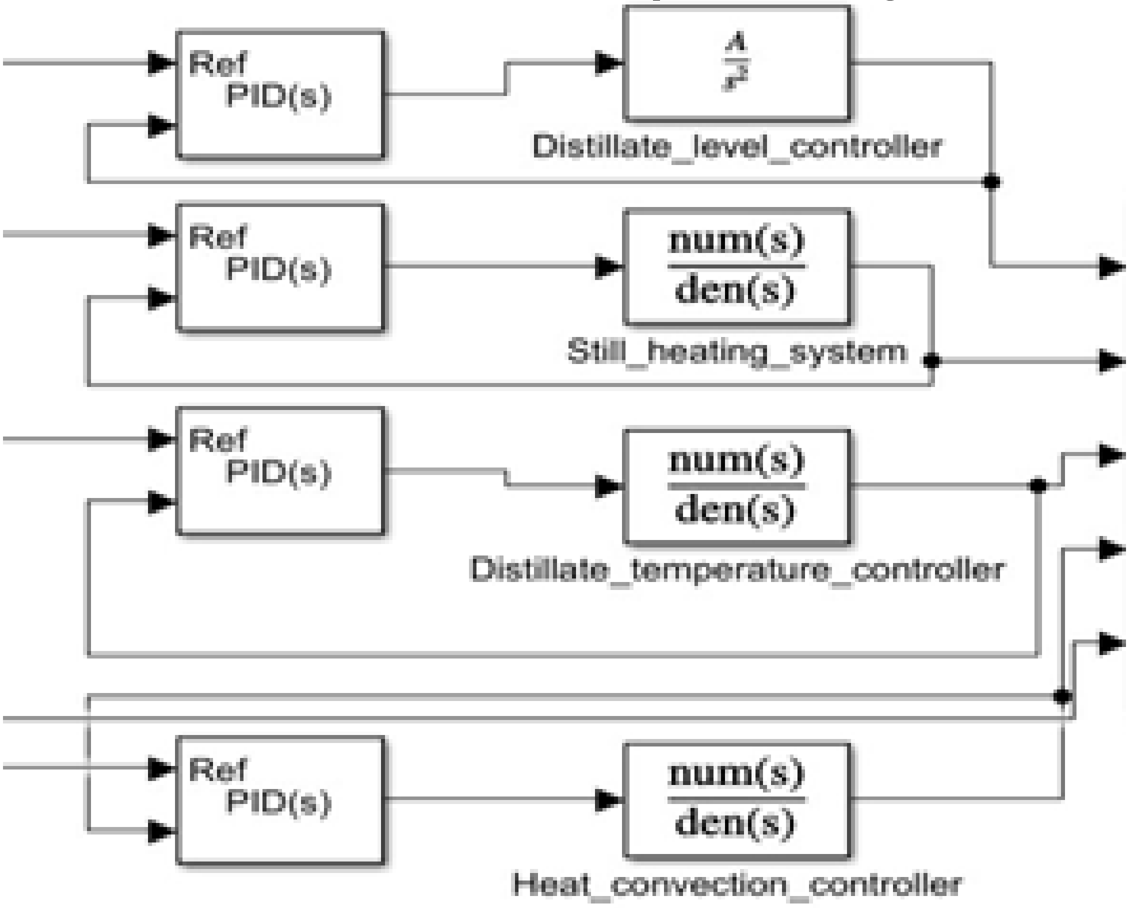


Figure 34: Simulation of MATLAB/SIMULINK Proportional Integral Differential (PID) transfer function models of the onboard processes

5 RESULTS AND DISCUSSIONS

5.1. DETERMINATION OF THE DESIGN SPECIFICATIONS

The design specifications for the feasibility incremental prototype were successfully determined from the literature review, benchmarking the performance specifications from existent similar distillers on market as well as the consumer needs data research and analysis from lead users of distiller technologies such as Prof Bioresearch Company Limited (Ug). The design specifications for the feasibility incremental prototype are detailed in the *Target Product specifications* section

5.2. DEVELOPING OF CONCEPTUAL AND DETAILED DESIGNS OF A LESS LABORIOUS DISTILLER

Automation was successfully applied to curb the laborious nature of the existent mainstream distillers which are manual in nature and always need an operator to care for the distillation process. This study employed Proportional Integral Differential (PID) controllers in closed loops to achieve servothermodynamic and servomechanic behaviors of the feasibility incremental automated multipurpose distiller prototype as discoursed in the *Product design* chapter.

5.3. DESIGNING THE HARDWARE CONTROLLER SOFTWARE FOR OPTIMAL ENERGY-EFFICIENCY DISTILLATION

State of the art engineering hardware programming tools such as MATLAB/SIMULINK were used ro develop, validate, optimize and deploy sophisticated hardware control programs which constituted of effective controllers such as the Proportional Integral Differential (PID) controllers as detailed in the *Software design* section

5.4. CONSTRUCTION AND TESTING OF THE FEASIBILITY INCREMENTAL PROTOTYPE

The feasibility distiller prototype was successfully constructed mostly by welding and fabrication of high strength parts as well as soldering low strength parts such as electrical connections. The feasibility distiller prototype was finally tested through virtual tests such as debugging for the hardware controller software, calibration tests for onboard sensors and actuators as well as holistic hardware field tests for the whole prototype as shown in the figure below whereas the summary of the timeline of execution of the implementation of the design of the feasibility distiller prototype is shown in *Appendix A*

Figure 35: Construction and testing of the feasibility distiller prototype

5.5. SUMMARY

As seen in the figure below, several achievements as well as failures were reached after the construction and testing of the feasibility incremental prototype

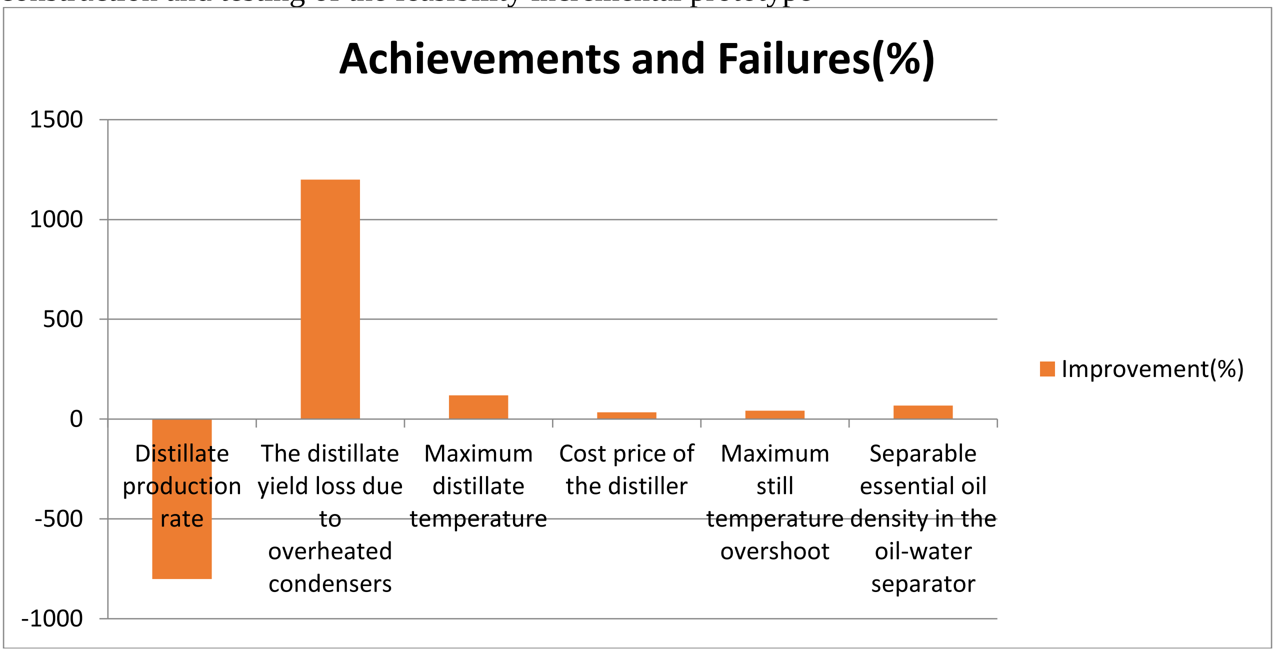


Figure 36: Summary of achievements and failures

From the bar graph above, the distillate production rate among other design specifications had an adverse performance of an 800% reduction from the benchmarked distillate production rate of 1g/s of distillers of similar still capacity. This was largely due to the worn-put and inefficient heater coil that was used to heat the still and thus never met the 3kW heater power specification as per the prototype's design.

On the other hand, there were remarkable improvements in the rest key specifications that is, the 118% reduction in the maximum distillate temperature and thus the 1200% reduction in the

distillate yield loss due to overheated condensers, the 33.3% reduction in the cost price of the distiller due to the material-optimised design and the local sourcing of consumables and materials, the 42% reduction in the maximum still temperature overshoot due to the incorporation of automation in the prototype as well as a 68% increment in the range of separable essential oil density in the oil-water separator.
The table shown below summarizes the results of the implementation of the design, construction and testing of the prototype of the multipurpose distiller

Specification	Benchmarked value	Achieved value
Distillate production rate	1.000g/s	0.111g/s
The distillate yield loss due to overheated condensers	13%	< 1%
Maximum distillate temperature	70^{0}C	32^{0}C
Cost price of the distiller	Shs.5,200,000/=	Shs.3,900,000/=
Maximum still temperature overshoot	40%	28%
Proof of ethanol distillation	90%	-
Separable essential oil density in the oil-water separator	300kg/m^3 -900 kg/m^3	200kg/m^3 - 2,100 kg/m^3

Table 14: Summary of the results of the design, construction and testing of the prototype of the multipurpose distiller

The figure below shows progression timeline of the implementation of the construction of the prototype of the multipurpose distiller

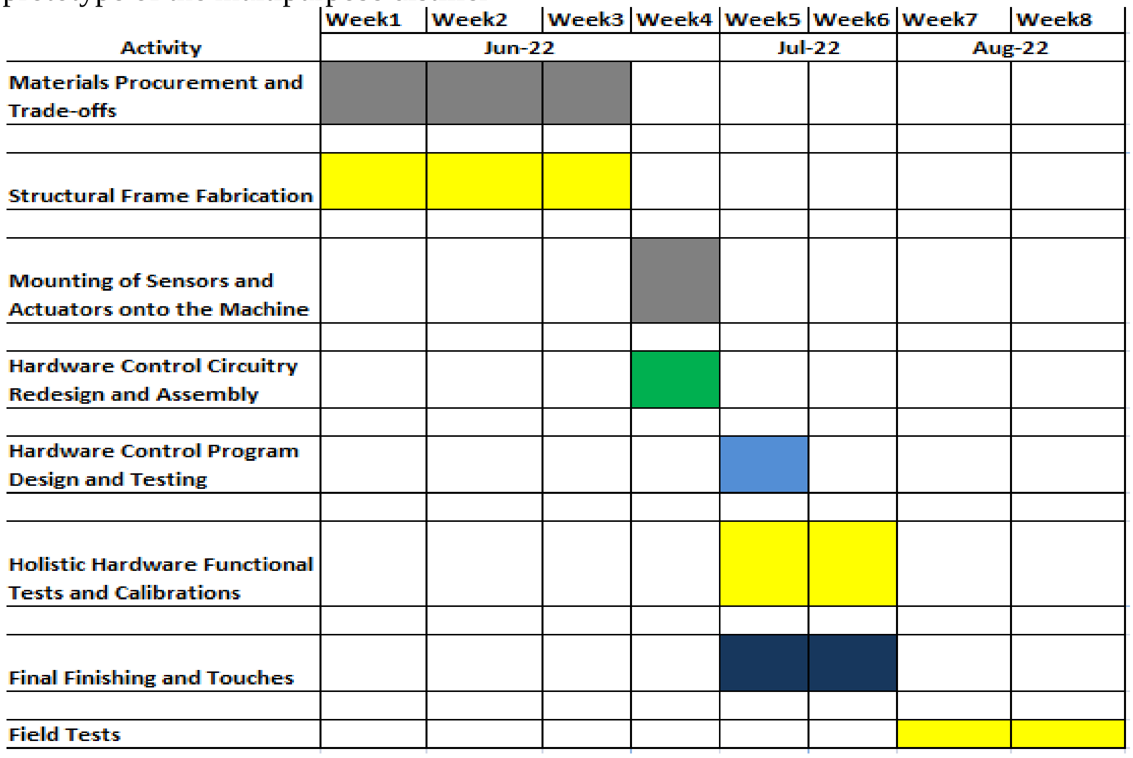


Figure 37: Gantt chart showing the timeline of the Project Implementation

6 CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

Uganda's steam distillation industry will be revolutionized by embracing this amazing robust Automated Multipurpose Distillation technology which flexibly allows dissimilar distillation processes to sequentially occur and moreover allows the stills to be heated by an auxiliary flame heat source separately. If adopted, the distillation technology presented herein will allow the production of high quality essential oils moreover at remarkably very low startup and running costs as compared to any other type of distillation processes since it optimizes by automation of the conventional water-steam essential oil distillation process. The automated essential oil distiller unlike the industrial dry steam distillers possesses no boiler (steam generator) which is notorious for increased heat loses yet it possesses the variable steam pressure, amount and temperature control of the conventional steam boiler and is thus more superior at energy efficiency. The Multipurpose Distiller technology discoursed herein is evidently much more cheaply replicable as it is made from locally available material while enabling automatically monitored energy consumption of the on-board distillation processes for optimal energy consumption as compared to mainstream essential oil distillers.
The main reason for choosing the automated water-steam essential oil distillation method is its potential neutrality to the chemical composition of the essential oil. Furthermore, it has proved to ensure the quality of the distillate product

6.2 RECOMMENDATIONS

6.2.1 RECOMMENDATIONS FOR FURTHER IMPROVEMENT AND RESEARCH

In order to minimize energy wastage in running the robust condenser's hardware that is the coolant pump and fan when they should not be actuates, the Proportional Integral Differential (PID) controllers for each process should be fine tuned using MATLAB/SIMULINK System auto-tuner function so as to obtain and deploy the Proportional Integral Differential (PID) controllers of the most optimized configuration
When replicating the hardware controller circuitry of the feasibility prototype of the multipurpose distiller, only one microcontroller that is, an Arduino Mega 2560 should be used instead of the two microcontrollers that is, the Arduino Uno and Arduino Nano so as to minimize any improvising such as the use of the onboard serial Controller Area Network which rather introduce more synergies in the implementation of the project work especially by interfering the fetching of sensors' feedback data
A MATLAB-compatible user-machine interface that is the Liquid Crystal Display (LCD) screen and input keypad shield should be used since MATLAB/SIMULINK's Arduino support package library provides no handy library for ordinary cheap Liquid Crystal Display (LCD) screens and input keypad shields or a custom MATLAB library for the ordinary Liquid Crystal Display (LCD) screens and input keypad shields should be constructed and published
To further reduce heat loss, the electric heaters should be used in favor of direct flame heat sources as well as insulating the stills with better insulating materials such as thick nylon sheaths.
An immersible electric heater should be used to reduce the heat energy lost to the environment by directly heating the still's contents
A food-grade material process line should be used that is, the still and condenser parts should all be made of either stainless steel or copper for safety
Because it is median-duty distillation equipment, the sources of the plant herbage raw material for essential oil distillation and the fermentation product and equipment should all be in the vicinity of the Multipurpose Distiller for economical running.

6.2.3 RECOMMENDATIONS TO THE STUDENT

Future designs of the distillation technology should be equipped with a more comprehensive and diversified essential oil composition detector in downstream of the condenser so that unwanted high boiling-temperature compounds and oxidations products are not be added to the distillate product.
Future designs of the distillation technology should be equipped with capabilities for automatic detection of essential oils that are hard to separate from water so that the user never needs to manually inform the distiller controller system about the presence of such essential oils.

6.3. RECOMMENDATIONS TO THE UNIVERSITY

The University community should invite and encourage corporate bodies and organizations with seasoned professionals in relevant fields to hold seminars and workshops that will enlighten the minds of the students on relevant developments and challenges in their discipline and potential professions. This would enable students develop more relevant solutions to the problems in society
As a way of encouragement, lecturers should use multimedia teaching aids when and where necessary as this would help students get a deeper understanding of the phenomena in their solutions projects to the problems in society.
Due to the nature of the nation's economy, the students should be funded in implementing their solutions projects.
More practical classes should be held so as to further reduce the breach between the classroom and the practical problems environment faced by the society. Field trips and excursions should be organized as this would encourage the students because the link between the classroom and potential field solution project ideas would be further emphasized

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APPENDIX

APPENDIX A: PROJECT'S EXECUTION TIMELINE

Weeks		Date	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Total
			Day of the Week						
Weeks	August	03/08/2020 - 08/08/2020	2.5 Hours	6.2 Hours	10.5 Hours	3 Hours	12Hours	6 Hours	42.5 Hours
Weeks	August	10/08/2020 - 15/08/2020	11 Hours	10.7 Hours	6 Hours	10 Hours	8 Hours	7.5 Hours	53.2 Hours
Weeks	July-August	19/08/2020 - 24/08/2020	8 Hours	6 Hours	4 Hours	8 Hours	6 Hours	10 Hours	42 Hours
Weeks	July-August	24/08/2020 - 29/08/2020	6 Hours	8 Hours	10 Hours	6 Hours	5 Hours	8 Hours	43 Hours
Weeks	July-August	31/08/2020 - 05/09/2020	6.5 Hours	10.5 Hours	10 Hours	10 Hours	8 Hours	8 Hours	53 Hours
Weeks	July-August	07/09/2020 - 12/09/2020	11 Hours	12 Hours	11 Hours	10 Hours	8 Hours	12.5 Hours	64.5 Hours
								OVERALL TOTAL	411.1 Hours

KEY	<5 Hours	5 to 10 Hours	>10 Hours

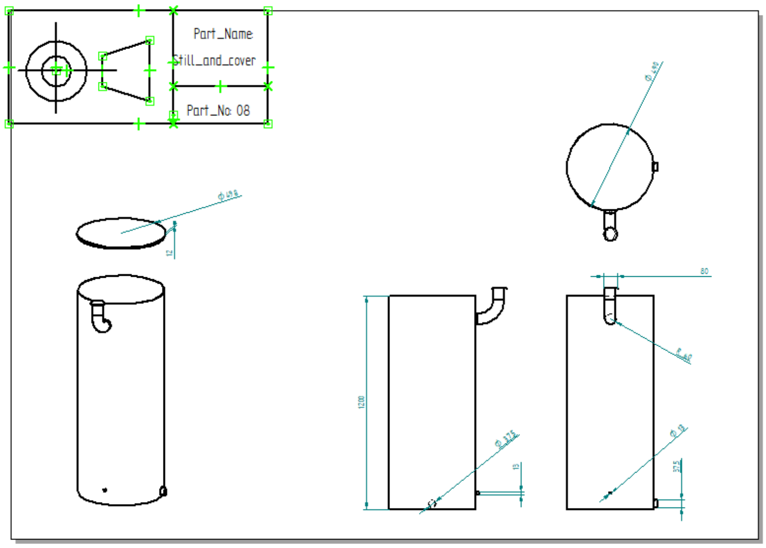
APPENDIX B: ANALYTICAL PARAMETRIC MACHINE DESIGN

THE STILL

$$H_b = Boiler\ height$$

$$H_b = V_b{}^2 \pi r^2$$

where: ‘r’ is the boiler radius (m) and V_b is boiler volume (m^3).



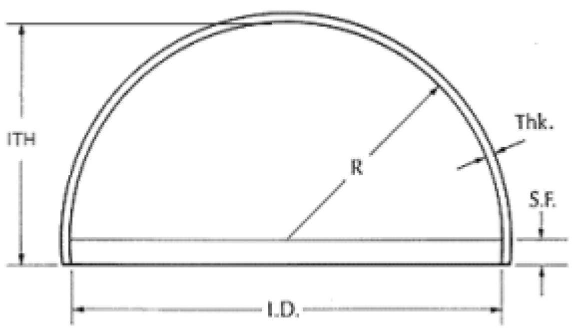
The still was finally designed as shown in the figure above

THE FRACTIONATING COLUMN

Thickness of shell: As per ASTM standards UG-27 the thickness of internally pressurized vessel is

$$tp = PD\ 2SE - P + C$$

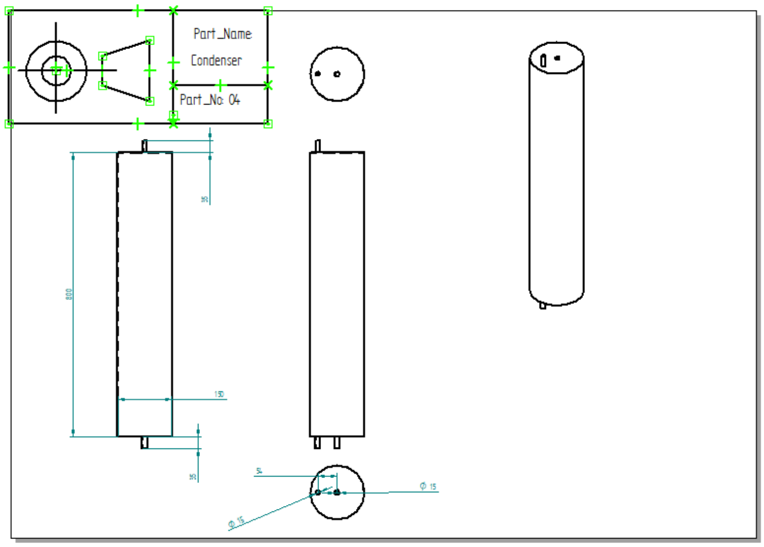
Where tp is shell thickness (in),
P is max allowable working pressure (psi),
D is inside diameter (in),
S is min allowable tensile stress (psi),
E is weld joint efficiency, and
C is corrosion allowance.
Hemispherical Head, on both top and bottom as shown in the figure below



THE CONDENSER

The shell thickness is designed similarly to the fractionating column’s thickness
As per ASTM standards UG-27 the thickness of internally pressurized vessel is

$$tp = PD\ 2SE - P + C$$



The condenser was finally designed as shown in the figure above

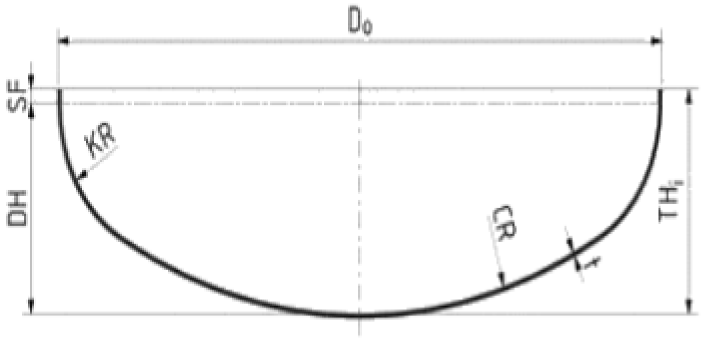
THE LIQUID-LIQUID (OIL-WATER) SEPARATOR

As per ASTM standards UG-27 the thickness of internally pressurized vessel is

$$tp = PD\ 2SE - P + C$$

For vessel heads, both ends are chosen ellipsoidal. Shape is shown in figure below

Figure 19: Ellipsoidal Vessel and Heads



APPENDIX C: SYSTEM CONFIGURATION PARAMETER COMPUTATIONS

The numerical results of calculations in Appendix A were computed in a spreadsheet program and are summarised below

Computation for Essential Oil Still, same for Ethanol Still					
System_Parameter	**Shreshold_Design_Value**	**Lower_Value**	**Upper_Value**	**SI_Unit**	**Remark**
P_still	39.57333	19.78667	59.36000	kW	SteadyState_Heat_into_still
Q_cond	0.33100	0.16550	0.49650	kW	Steady_Heat_transfer_through_condensor_tube
d_c	0.06000	0.00986	0.09000	m	Column_diameter
D_cond_t	0.01500	0.00750	0.02250	m	Diam_of_condensor_tube
D_cool_t	7.65462	3.82731	11.48193	m	Diam_of_coolant_tube
l_c	0.90000	0.45000	1.35000	m	Length_of_column
H_pump	4.00000	2.00000	6.00000	m	Head_of_coolant_pump
P_pump	0.00074	0.00037	0.00110	W	Power_of_pump
t_still	2.14132	1.07066	3.21199	mm	thickness_of_still_wall
V_still	226.38000	--	--	Ltr	Design_Volume_of_Still
D_still	490.00000	--	--	mm	Diameter_of_still
H_still	1200.00000	--	--	mm	Height_of_still
V_r_still	200.00000	--	--	Ltr	Rated_Still_Volume
H_resv	13.98357	--	--	mm	Reserved_still_height
t_r_still	3.00000	--	--	mm	Design_thickness_of_still_wall
D_c	0.06000	--	--	m	Design_column_diameter
Q_rad	0.82750	0.41375	1.24125	kW	Design_Radiator_Power
Q_rad_r	0.50000	0.25000	0.75000	kW	Rated_Radiator_Power
LMTD_cond	19.56974	9.78487	29.35460	K	Condenser_LMTD
1/U_cond	0.00250	0.00125	0.00375	W/m^2C	1/U_of_condenser_tube
A_cond_tube	0.04228	0.02114	0.06343	m^2	Circumferential_condenser_tube_area
l_cond_tube	0.89695	0.44847	1.34542	m	Length_of_condenser_tube
Computations_for_Essential_Oil_Boiler					
System_Parameter	**Shreshold_Design_Value**	**Lower_Value**	**Upper_Value**	**SI_Unit**	**Remark**
H_b_pump	4.1315	2.06575	6.19725	m	Head_of_boiler_pump
P_b_pump		0.00000	0.00000	W	Power_of_boiler_pump
P_boiler	0.1067	0.05333	0.16000	kW	Steady_Heat_into_boiler
d_b_pipe	0.0088	0.00438	0.00219	M	Diameter_of_boiler_downstream_pipe
Rad_LMTD	0.9941	0.49707	0.24853	K	LMTD_of_Radiator
1/U_rad	0.0040	0.00200	0.00100	W/m^2C	1/U_of_Radiator
A_rad	1.3318	0.66590	0.33295	m^2	Effective_Radiator_Area
l_cu_rad	28.25051	14.12526	7.06263		Length_of_Copper_tube_Radiator

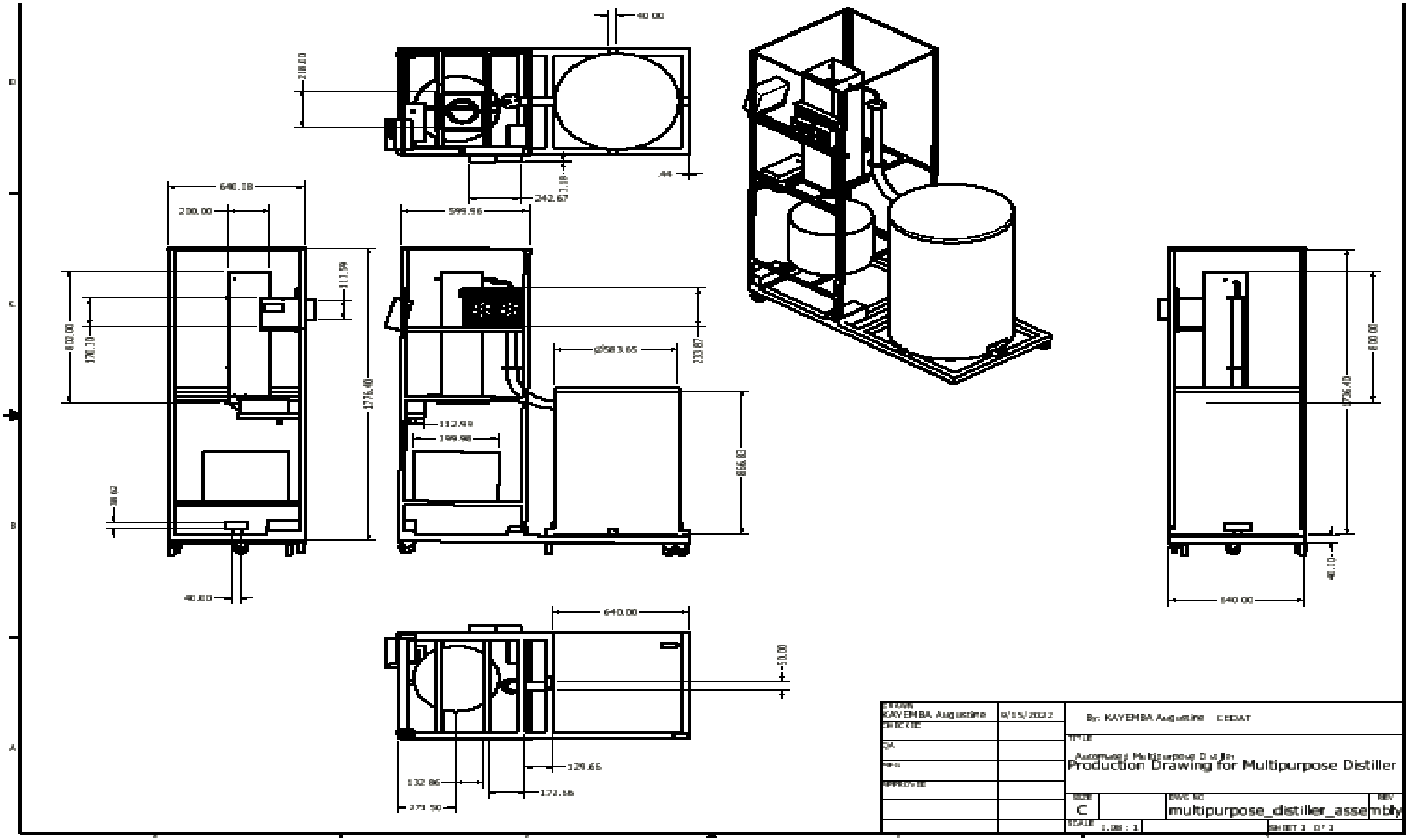
Independent_Parameters			
Parameter_Name	**Value**	**SI_Unit**	**Remark**
m_0	0.001111	kg/s	Distilate_mass_flow_rate
R_r	15.000000	-	Reflux_ratio
u_c	0.000350	m/s	Speed_of_coolant_water
h_still	2693.000000	kJ/kg	Enthalpy_of_steam_in_still
h_brew_ss	467.000000	kJ/kg	SteadyState_enthalpy_of_stillage
h_col1	300.000000	kJ/kg	Enthalpy_of_steam_in_condensor_upstream
h_prod	138.000000	kJ/kg	Enthalpy_of_liq_condesate
Pr_boiler	20265.000000	Pa	SteadyState_Boiler_Preassure
h_boiler	2706.000000	kJ/kg	Enthalp_of_downstream_boiler_steam
h_eo1	2700.000000	kJ/kg	Enthalpy_of_upstream_EO_still_stream
u_boiler	0.020000	m/s	speed_of_downstream_boiler_steam
H_cond_res	2.000000	m	Net_Height_between_condensor-reservior
m_c	0.000038	kg/s	Coolant_mass_flow
u_prod	0.010357	m/s	Speed_of_vapour_distilate_in_tube
P	1.020000	M Pa	Design_still_Circumferential_Pressure_Load
P_brew	0.340000	M Pa	Circumferential_pressure_load_in_brew_still
Constant_Parameters			
Parameter_Name	**Value**	**SI_Unit**	**Remark**
Re_298K	3000	--	Reynolds_no_for_water_at_25C
Re_343K	3000	--	Reynolds_no_for_water_at_70C
v_T_still	1.00E-07	m^2/s	Kinematic_viscosity_of_steam_in_still
v_343K	4.13E-07	m^2/s	Kinematic_viscosity_of_distilate_in_cond
v_298K	8.926E-07	m^2/s	Kinematic_viscosity_of_water_at_298K
alpha_still	0.1	(%)	Concentration_of_still_ethanol
Re_boiler	2500	--	Reynolds_no_for_steam_in_EO_boiler
T_prod	302	K	Distilate_temperature

T_col1	373	K	Column_downstream_steady_temp
T_still	373	K	Still_downstream_steady_temp
T_boiler	373	K	Boiler_downstream_steady_temp
Pr_still	151987.5	Pa	SteadyState_Preassure_in_still_downstream
T_eo1	390	K	Steady_Upstream_EO_still_temp
v_b_temp	7.00E-08	m^2/s	Kinematic_viscosity_of_steam_in_boiler
ro_still	0.8624	kg/m3	Density_of_steam_in_still
ro_boiler	1.1289	kg/m3	Density_of_steam_in_boiler
T_c1	299.9	K	Inlet_coolant_temp
T_c2	302	K	Outlet_coolant_temp
D_still	450	mm	Design_sstill_diam
z	0.8	--	Still_weld_joint_strength_factor
F_min	1.33E+02	M Pa	Minimum_design_force
FOS	3	--	Factor_of_safety
mu_still	2.79E-04		Viscosity_of_steam_in still
T_atm	299.5	K	Ambient_Atmospheric_Temperature
T_rad_air	3.00E+02	K	Heated_Radiator_Air_Temperature

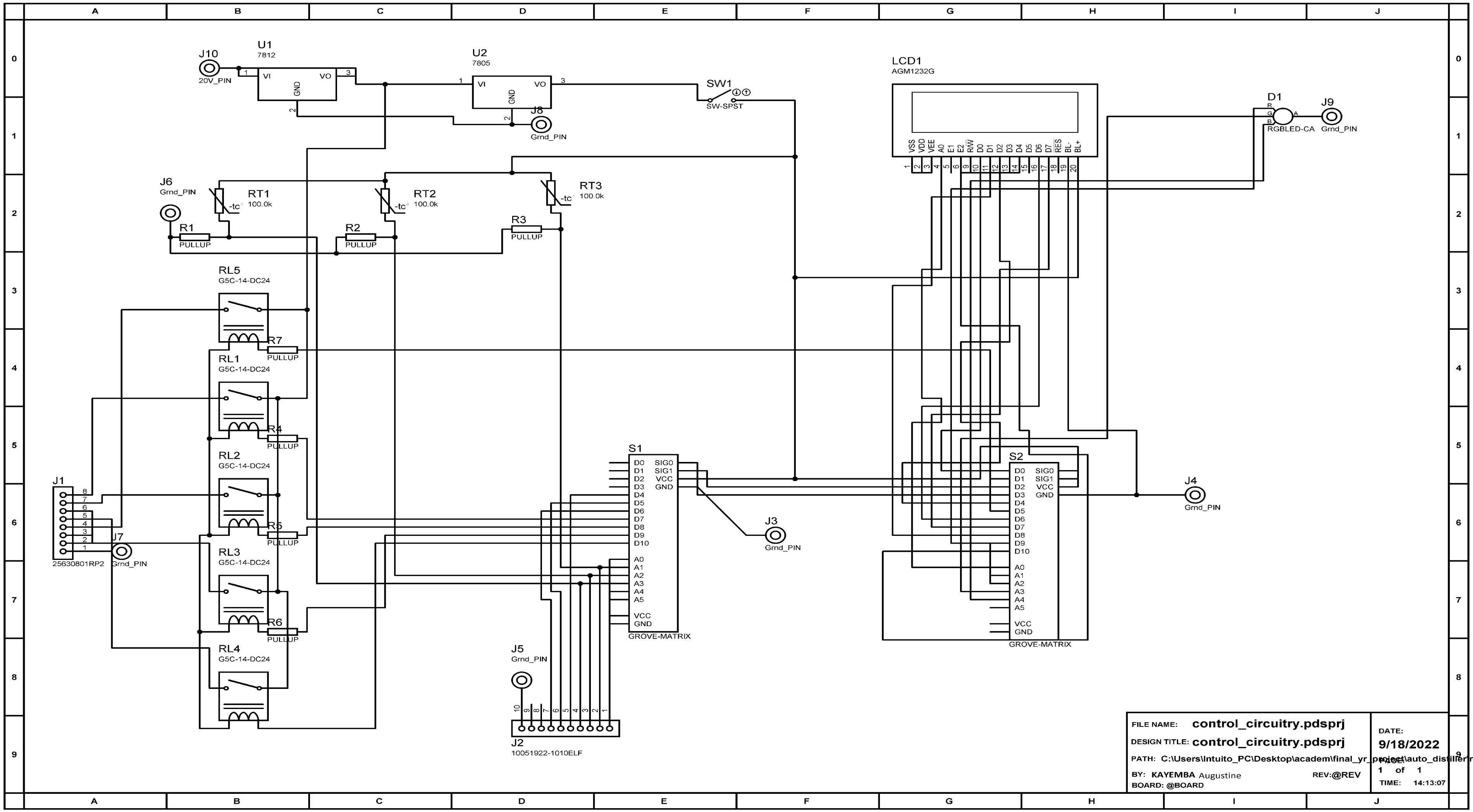
APPENDIX D: PROCESS CONTROLLERS' DESIGN AND VALIDATION

```
% variables declaration
A = 0.0085; % Cross sectional area of oil-water separator
c = 4200; % SHC of water
m_still = 10; % Mass of mixture in the still
m_coolant = 25; % Mass of coolant
h_conv = 50; % Convective coefficient at radiator
A_rad = 1.01; % Effective convective area of radiator
% Transfer functions
% Distillate level controller
Distillate_level_controller = tf(A, [1, 0, 0]);
% Still heating system
Still_heating_system = tf(m_still*c, [1, 0, 0]);
% Distillate temperature controller
Distillate_temperature_controller = tf(m_coolant*c, [1, 0, 0]);
% Heat convection controller
Heat_convection_controller = tf(h_conv*A_rad, [1, 0, 0]);
% Configuration validation in closed loop
% step responses
figure(1)
subplot(2,1,1)
step(1+Distillate_level_controller)
title("Step response of Distillate level controller in openloop")
subplot(2,1,2)
step(1/(1+Distillate_level_controller))
title("Step response of Distillate level controller with PID Controller")
figure(2)
subplot(2,1,1)
step(1+Still_heating_system)
title("Step response of Still heating system in openloop")
subplot(2,1,2)
step(1/(1+Still_heating_system))
title("Step response of Still heating system with PID Controller")
figure(3)
subplot(2,1,1)
step(1+Distillate_temperature_controller)
title("Step response of Distillate temperature controller in openloop")
subplot(2,1,2)
step(1/(1+Distillate_temperature_controller))
title("Step response of Distillate temperature controller with PID Controller")
figure(4)
subplot(2,1,1)
step(1+Heat_convection_controller)
title("Step response of Heat convection controller in openloop")
subplot(2,1,2)
step(1/(1+Heat_convection_controller))
title("Step response of Heat convection controller with PID Controller")
% Bode analysis
figure(1)
subplot(2,1,1)
bode(1+Distillate_level_controller)
title("Bode Plot of Distillate level controller in openloop")
subplot(2,1,2)
bode(1/(1+Distillate_level_controller))
title("Bode Plot of Distillate level controller with PID Controller")
```

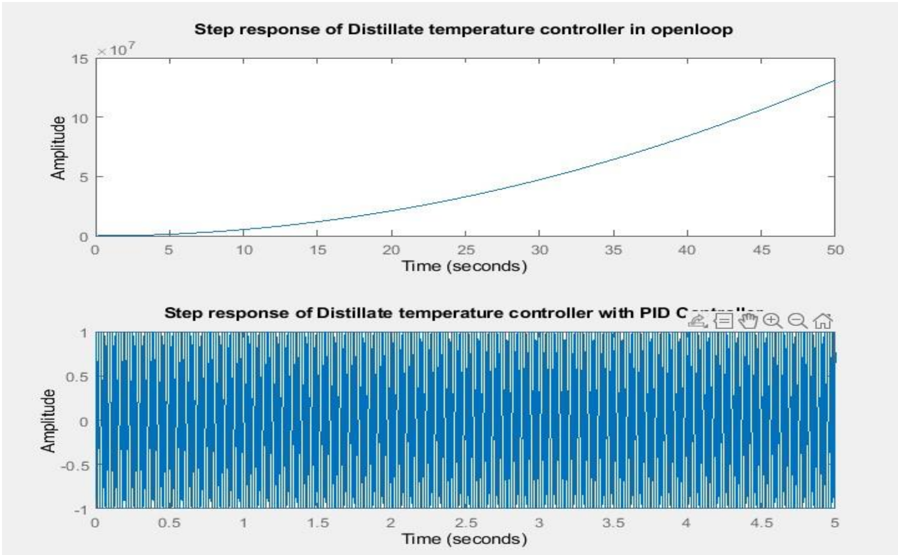
APPENDIX E: PRODUCTION DRAWING

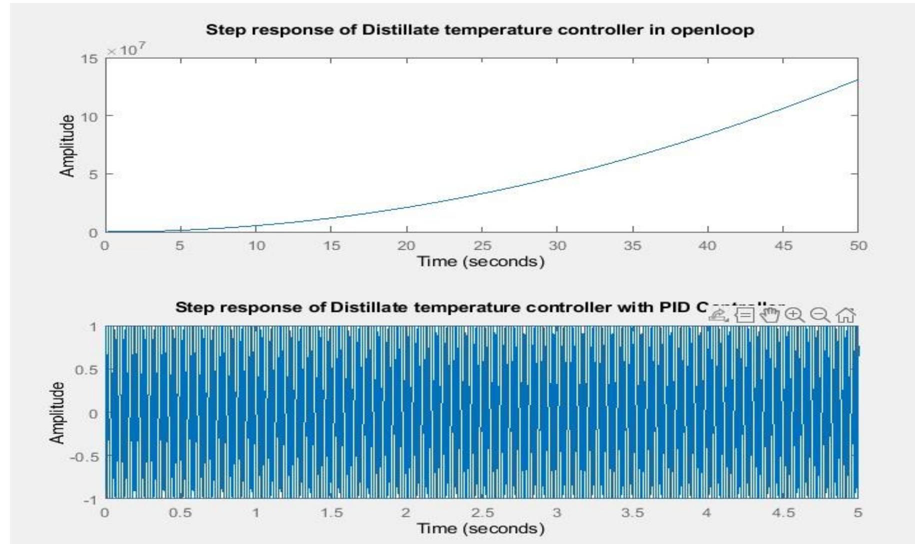


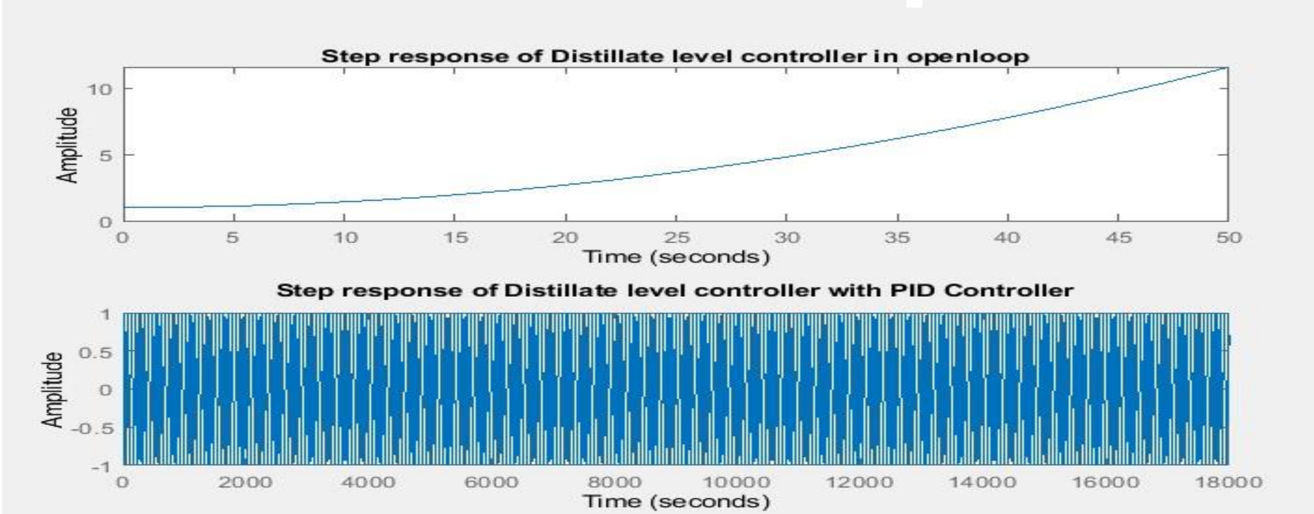
APPENDIX F: HARDWARE CONTROLLER CIRCUITRY DESIGN



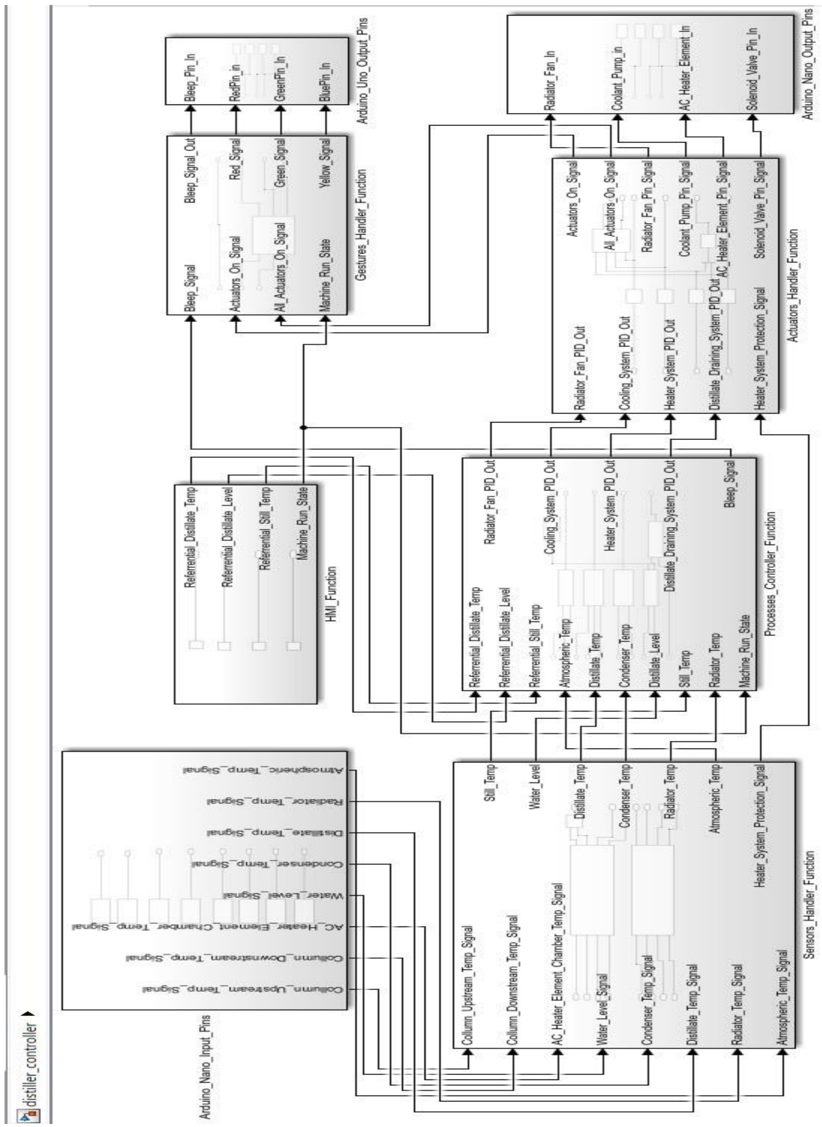
APPENDIX G: PROCESSES CONTROLLERS DESING CONFIGURATION VALIDATION







APPENDIX H: HARDWARE CONTROLLER SOFTWARE



ACTUATORS_MONITOR_FUNC

```
function [Red_Signal, Green_Signal, Yellow_Signal] =
fcn(Actuators_On_Signal, All_Actuators_On_Signal,
Machine_Run_State)
if Actuators_On_Signal > 0
%     Light yellow
        Yellow_Signal = 1;
else
    %     Light yellow off
        Yellow_Signal = 0;
end
if All_Actuators_On_Signal > 0
%     Light Red
        Red_Signal = 1;
else
    %     Light Red off
        Red_Signal = 0;
end
if Machine_Run_State == 0
%     Light Green in standby
        Green_Signal = 1;
else
    %     Light yellow oof
        Green_Signal = 0;
end
end
```

APPENDIX I: HARDWARE CONTROLLER SOFTWARE

ACTUATORS_SWITCH_STATES_MONITOR_FUNC

```
function [Actuators_On_Signal, All_Actuators_On_Signal]
= fcn(u1, u2, u3, u4)
% Initiate defaults
Actuators_On_Signal = 0;
All_Actuators_On_Signal = 0;
% Check actuators switch states
if (u1 + u2 + u3 + u4) < 1
%     All_Actuators_On_Signal = 0; % Check if all
actuators are on
    Actuators_On_Signal = 0;
elseif (u1 + u2 + u3 + u4) > 0 && (u1 + u2 + u3 + u4) <=
3.1
    Actuators_On_Signal = 1; % Check if an actuator is on
end
    if (u1 + u2 + u3 + u4) > 3.5
    All_Actuators_On_Signal = 1; % Check if all actuators
are on
    else
       All_Actuators_On_Signal = 0; % Check if all
actuators are on
end
end
```

ANALOG_SENSORS_HANDLER

```
function [Collumn_Upstream_Temp, Collumn_Downstream_Temp,
AC_Heater_Element_Chamber_Temp, Water_Level,
Heater_System_Protection_Signal] = fcn(Collumn_Upstream_Temp_Signal,
Collumn_Downstream_Temp_Signal, AC_Heater_Element_Chamber_Temp_Signal,
Water_Level_Signal)
% Analog Temp Sensors Constants
THERMISTORNOMINAL = 90000;
TEMPERATURENOMINAL = 298; % 25 dge_C
BCOEFFICIENT = 3950;
SERIESRESISTOR = 10000; % R_1

% Temp sensor 1
R_1 = SERIESRESISTOR*(Collumn_Upstream_Temp_Signal/1023)/(5 -
(Collumn_Upstream_Temp_Signal/1023)*4.99); % NTC Resistance
Collumn_Upstream_Temp = 1/(1/TEMPERATURENOMINAL -
log(abs(THERMISTORNOMINAL/R_1))/BCOEFFICIENT) -273; % Compute temp
% Temp sensor 2
R_2 = SERIESRESISTOR*(Collumn_Downstream_Temp_Signal/1023)/(5 -
(Collumn_Downstream_Temp_Signal/1023)*4.99); % NTC Resistance
Collumn_Downstream_Temp = 1/(1/TEMPERATURENOMINAL -
log(abs(THERMISTORNOMINAL/R_2))/BCOEFFICIENT) -273; % Compute temp
% Temp sensor 3
R_3 = SERIESRESISTOR*(AC_Heater_Element_Chamber_Temp_Signal/1023)/(5 -
(AC_Heater_Element_Chamber_Temp_Signal/1023)*4.99); % NTC Resistance
AC_Heater_Element_Chamber_Temp = 1/(1/TEMPERATURENOMINAL -
log(abs(THERMISTORNOMINAL/R_3))/BCOEFFICIENT) -273; % Compute temp

% Water level sensor
Water_Level = Water_Level_Signal/1023*100;

% Heater System Protection
if AC_Heater_Element_Chamber_Temp > 160
    Heater_System_Protection_Signal = 1;
else
    Heater_System_Protection_Signal = 0;
end
end
```