ASHESI UNIVERSITY COLLEGE

AN AUTOMATIC RETRACTABLE CLOTHES DRYING RACK

CAPSTONE PROJECT

B.Sc. Mechanical Engineering

Haddijatou Touray

2019

ASHESI UNIVERSITY

AN AUTOMATIC RETRACTABLE CLOTHES DRYING RACK

CAPSTONE PROJECT

Capstone Project submitted to the Department of Engineering, Ashesi University in partial fulfillment of the requirements for the award of Bachelor of Science degree in Mechanical Engineering.

Haddijatou Touray

2019

DECLARATION

I hereby declare that this capstone is the result of my own original work and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature:

………………………………………………………………………………………………

Candidate's Name

………………………………………………………………………………………………

Date:

………………………………………………………………………………………………

I hereby declare that the preparation and presentation of this capstone were supervised in accordance with the guidelines on supervision of capstone laid down by Ashesi University.

Supervisor's Signature:

………………………………………………………………………………………………

Supervisor's Name:

………………………………………………………………………………………………

Date:

………………………………………………………………………………………………

Acknowledgments

All praise is due to Allah (SWT) the Almighty for his continuous support and blessings in making this capstone project successfully completed.

I would like to deeply and sincerely thank my supervisor, Dr. Kenobi Morris. His tireless effort and motivation from the project inspection to completion have extremely inspired me. I would also like to thank him for his kindness and empathy.

I am extremely grateful to my parents for their prayers, love and care, and sacrifices in my education. This capstone would not have been successful without their deep prayers and encouragement. Thank you sister Aminah and brother Ebrihim for your tireless effort in making my university life fruitful.

I am extending my heartfelt thank you to the entire Engineering Department of Ashesi University. Special thank you to Dr. Nathan Amanquah Dean of Engineering, Ashesi workshop assistants: Nicholas Tali, Joseph Timpabi, and Peter Lawerh, for their immense help in the successful navigation through the workshop and with all workshop tasks of the capstone and as well as the encouragement.

Finally, I thank everyone who has in one way or the other supported me to get this capstone completed.

Abstract

Working adults and university students find it difficult to complete their laundry in a day because of the unpredictable weather conditions in the tropics of West Africa. There are existing drying machines, but these machines are either not smart or they are hard to install and maintain and they cause easy damage to the clothes. In comparison to the United States where electric drying is mostly used, about 16 billion kW is consumed per year or 5.8% of the whole resident electricity consumption. Equating this electricity consumption rate to that of West Africa, it will be very expensive for an average student or working adult to afford.

This capstone project presents the design and prototype fabrication of automatic retractable clothes drying rack that facilitates the drying of clothes in highly humid and rainy environments. The automatic retractable clothes drying rack is divided into four parts: The drying rack frame, the linear actuator, sensors, and motor controls, and the cover curtain mechanism. The drying rack frame is a scissors-like mechanism, that releases and exposes the clothes based on the weather conditions of the environment.

This paper entails the processes taken in coming up with the design, the prototype implementation, the result and analysis from the prototype testing, and some suggested future work.

Table of Content

List of Figures

List of Tables

Nomenclature

Symbol	Name
E	Young's Modulus or Modulus of Elasticity
σ	Stress
ε	Strain
W1	Weight of a wet towel
W2	Weight of a wet pair of jeans
W2	Weight of a wet cotton dress
W_{total}	The total weight of the clothes
T_1 and T_2	Reaction forces at the ends of one hanging rod
F_{max}	Maximum applied force on one drying line
F_{min}	Minimum applied force on the drying line
Δl	The elongation of the material
l_o	The original length of the hanging rod
%E	Percentage elongation
M	Moment force
V	Shear force
M_{mean}	Midrange bending moment
M_a	Amplitude bending moment
σ_{mean}	Midrange bending stresses
σ_a	Amplitude bending stresses
S_y	Yield strength
n_f	The factor of safety due to fatigue
m	Mass
m_{totalC}	Total mass on the three hanging rods due to the clothes
V_{totalF}	The total volume of the drying line frame
m_{totalF}	The total mass of the drying line frame
m_{total}	Mass of the drying line frame and the clothes
P	Power
V_{pk}	Peak Linear Velocity
T_f	The torque due to friction
T	The torque due to gravity
T_{ext}	The torque due to external fore
μ	Coefficient of friction
n_s	The efficiency of the system
J_t	Total inertia
J_L	Load inertia
J_s	Leadscrew inertia
α	Angular acceleration
a	Linear acceleration

Chapter 1: Introduction

1.1 Background and Problem Definition

Most West African countries like Ghana, Nigeria, Sierra Leone, Cote d'Ivoire, The Gambia, and many others lie in the tropical areas with two seasons; rainy and dry. Ghana, in particular, has a typical tropical monsoon climate with about 750 mm annual rainfall [1]. Rainy seasons and humidity are inevitable, and they can cause a delay in human activities. For instance, washed clothes take longer to dry during the rainy season especially when working adults or students leave the house, leaving their clothes on the line for drying, and the clothes get soaked continuously by the rain. During the rainy season, it is often hard to predict the change in the weather condition. Hence, working adults and students find it difficult or impossible to get laundry clothes dried on the same day[2]. This causes delays in their activities and imposes constraints on the choices of clothes to be worn on a specific day.

There are hot drying racks, clothes laundry dryers, irons, hydro laundry, and outdoor drying racks. These existing drying machines or equipment are either not smart or they are expensive to install and maintain and they cause easy damage to the clothes [3].

In comparison to the United States where electric drying is mostly used, about 16 billion kW is consumed per year or 5.8% of the whole resident electricity consumption [4]. Equating this electricity consumption rate to that of West Africa, it will be very expensive for an average student or working adult to afford.

Therefore, there is a need for and the interest in an alternative, efficient and affordable clothes drying mechanism for residence in the tropics of West Africa, where the rainy season is predominant.

1.2 Objectives of the Project Work

This project seeks to design and fabricate a prototype of automatic retractable clothes drying rack. Unlike the existing clothesline, these clothes drying rack will be cost-effective, durable, efficient, and simple. The device will expose or cover the clothes based on environmental conditions such as rainfall, sunshine, and humidity. The summary of the objectives that the automatic retractable clothes drying rack seeks to achieve are as follows:

- Facilitate the drying of clothes in highly humid and rainy environments in West Africa.
- Cut down the cost incurred in buying and maintaining clothes drying machines or equipment.
- Help maintain the quality of clothes by proving natural and efficient clothes drying technique.

1.3 Expected Outcomes of the Project Work

The expected outcome at the completion of this project is a user-friendly, cost-effective, simple, and efficient system, that retrieves and releases the hanging clothes based on the weather conditions. Also, the design must have water proved cover curtain that spreads out to completely cover the clothes when raining. The best design system is in for major components:

- A seesaw-like mechanism of a drying rack frame with hanging rods.
- A control unit with Arduino Uno, a DHT22 humidity sensor, a water sensor, a Light Depended Resistor (LDR), and two stepper motors, to control the movement of the clothes drying rack.
- Two linear actuators to facilitate the linear motion of the structure.

- A waterproofed curtain rolled over a rod, coupled to a stepper motor and gears, to cover up clothes after retrieval during unfavorable weather conditions.

1.4 Justification/Motivation for Project Topic

During my four years at Ashesi University, I and my colleague have experienced the pain in leaving your clothes on the drying line to dry-up while in class, and the clothes get soaked by the rain. The outdoor clothes dryers are completely manual and have no protection for the clothes during unfavorable weather conditions. We could not afford an electric clothes dryer because it is expensive to install and maintain. In addition, electric dryers expose the clothes to a higher temperature range of 90° F up to $170\ ^{\circ}$F which caused easy damage to clothes[4]. Therefore, the automatic retractable clothes drying rack is the best solution to these challenges.

Chapter 2: Literature Review

2.1 Review on Existing Clothesline Designs

Washed and wet clothes are suspended onto drying lines with pegs or hangers, to be dried up by the combination of air, wind, sunlight, and gravity, slowly breaking the bond between the water molecules and to the clothes. The wet clothes can also be put in machines to be dried using electric energy. This section of the write up reviewed some of the existing clothesline designs to evaluate and appreciate the work done in this domain.

2.1.1 Outdoor Retractable Laundry Hangers

These systems facilitate the drying of clothes either under the sun or indoors when it rains. They are user-friendly and mostly equipped with German technology and parts. They are highly designed for residents with space constraints. Some of these devices sit flat, locked at the upper and lower positions on the ceiling when not in use. Others are wall-mounted and can manually retrieve and release the clothes [5]. These devices (Figure 2.1) make your home look neater and provide space for movement. They are highly available on online shopping platforms. However, these systems are not automatic, they work manually.

Figure 2.1: Outdoor retractable laundry hangers

2.1.2 An Automatic Cloth Retrieval and Drying

The Automatic cloth retrieval and drying reviewed in this section (Figure 2.2), was developed in 2017 by four Mechanical Engineering students from Bannari Amma Institute of Technology, India. The system was designed to fit well into the Indian environment, using a solar energy source. A sheet metal, an electric motor, a solar panel and more were used to develop an entire automatic drying line, powered using solar cells. The drying line had sensors like the rain detector, proximity sensor, and a control unit, to monitor and control the retrieval in and out of the drying line. The drying time of the clothes is set up using a push button and it automatically retrieves the clothes using a DC motor when the drying time is finished [2]. The design included all necessary components for an automatic drying line, but it was spacious and hence would not be preferable in homes where space is a limitation.

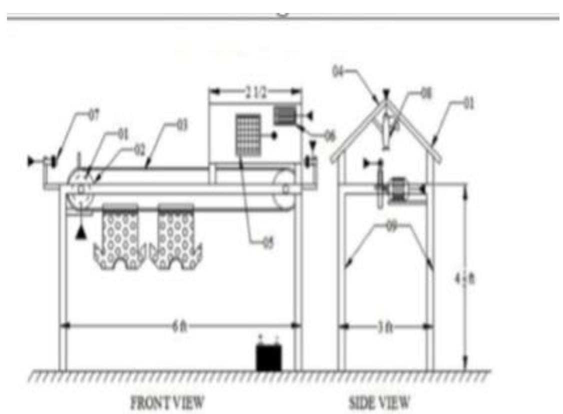
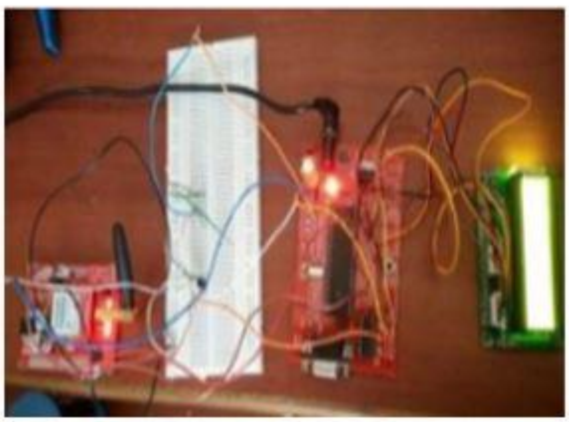


Figure 2.2: Automatic Clothes Retriever

2.1.3 Automatic Protection of Clothes and Automatic Clothes Retriever System

These clothesline designs (Figure 2.3) focused on the electronics and automation of retractable clothesline. The Automatic Protection of Clothes from Rain used Keil micro vision and microcontroller-based sensor units to control the moving tray. Sensor circuit, DC Relays, and ULN 2803 driver were added in the hardware part of the system [6]. Unlike the Automatic Protection of Clothes from Rain, the Automatic Clothes Retrieval System used microcontroller P1C16F877A to install all programs needed to give instructions to the drying line. It used a DC motor, a Light Dependent Resistor (LDR), a temperature sensor and a rotary knob switch, to develop the technique that retracts the clothes when it is sunny and retrieves the clothes when it is rainy [7]. Both designs were built and tested in India. These designs will be useful in the automation and control phase of my project only because there was no mechanical building of the actual drying line structure.



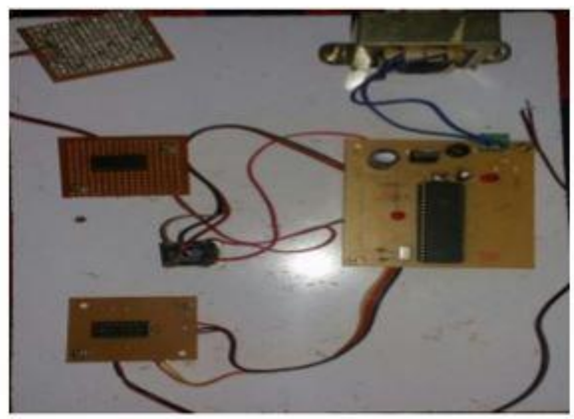


Figure 2.3: A control for automatic control of clothes from rain

2.1.4 Design of Intelligent Hanger Based on Single Chip and Pro-Engineering

Two students from Nanchang Institute of Technology, China, designed and fabricated an intelligent hanger (Figure 2.4) in 2013. This design used a single chip and Pro-E software. The design had a cover curtain that rolls up and down through the driving of the motor. The AT89C52 single chip, a rain sensor, two stepper motors positive and negative and a temperature sensor were used to control the system. Hangers will automatically open or close based on the temperature of the surrounding [3]. However, the product is a stand and can occupy a lot of space. The design did not involve the humidity sensor.

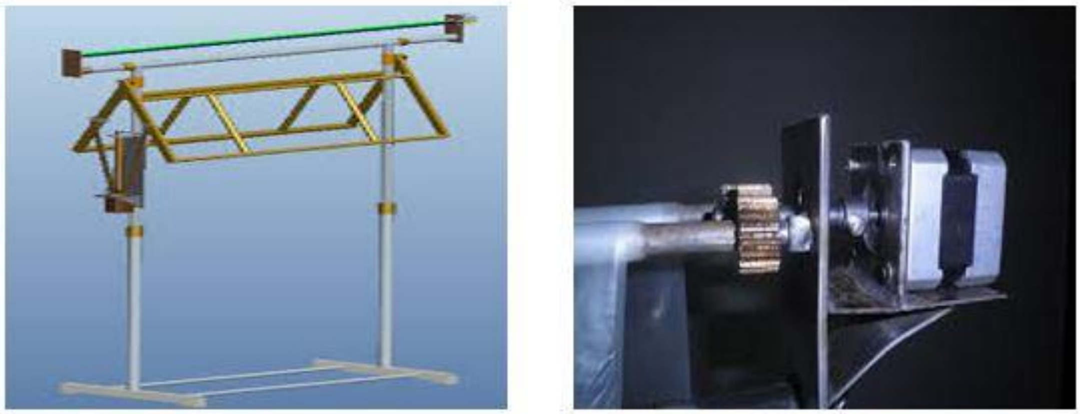


Figure 2.4: Solid Works design of an intelligent hanger and cover curtain control

2.2 Summary from the Literature Review

The common gaps identified in the existing drying lines based on the literature include the manual operation of the drying line which causes a delay in drying the clothes. There are also incomplete designs of automatic drying lines which causes limited literature for researchers and engineers. In addition, some of the designed drying lines did not include all the necessary sensors for complete automatic retraction and retrieval of the hanging clothes. For example, the Intelligent Hanger Based on Single Chip and Pro-Engineering did not include the humidity sensor and this will affect the proper functionality of the drying line especially in highly humid areas. Moreover, all the reviewed literature were devices developed in areas far from West Africa. Therefore, unlike the existing clothes drying mechanisms, the Automatic retractable clothes drying rack is user-friendly, cost-effective, simple, and efficient. The aim of the product is to make the drying of clothes in highly humid and rainy environments in West Africa possible.

Chapter 3: Methodology 1 - Design

3.1 Design Objectives

The automatic clothes drying rack design was evaluated under certain criteria. The criteria used in evaluating the design concepts include the availability of materials/components, cost of materials, simplicity of the design, ease of use, and size of the system.

The system was designed with easily available and less costly materials. The system must also be simple, easy to use and sizable for affordability, and to occupy less space in dormitories and homes.

3.2 Three Initial Design Concepts with Frame Sketched

Design concept 1: Drying lines inside a locker

This drying line (Figure 3.1) is a mini locker with two doors, four rotating wheels, three movable drying lines, and a metallic sliding cover at the top of the locker as a cover for the lines when inside the locker. When the device is in operation, the locker doors open, and the user can hang clothes on the lines. The drying locker is then moved outside. When it is not raining, and the environment is not humid, the sliding lit on the top of the mini locker opens and drying lines are moved vertically outwards to receive the sunshine. When the environment is humid or is raining, the drying lines move downwards inside the locker, and the locker's sliding metallic cover closes. The up and downward movements of the drying line are based on the weather condition. The metallic cover of the locker is made up of solar cells to power the motor needed for the upward and downward movements of the drying lines.

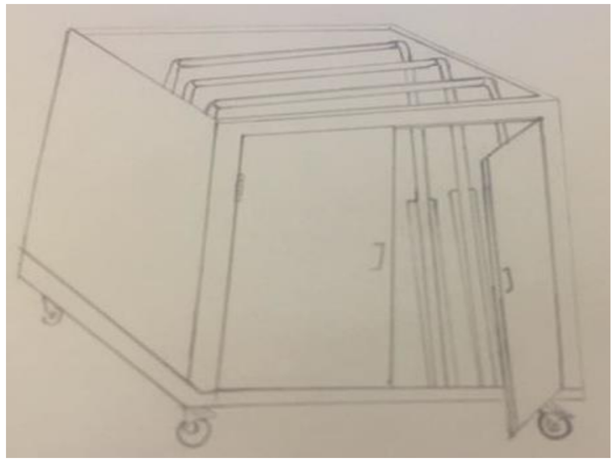


Figure 3.1: Hand sketch of concept 1

Design concept 2: Wall mounted retractable clothes drying rack

The wall mounted retractable clothes drying rack (Figure 3.2) comprises of three hanging rods attached and connected to a seesaw-like rectangular structure. The structure and the hanging rods will be attached to the wall depending on the direction of the sun and the wind. At the far edge of the rectangular structure is a curtain folded around a rod. When clothes are on the hanging rods and it is neither raining nor humid, the rectangular structure releases to direct the clothes to the sun. When it is raining, the rectangular structure retracts, and the curtain unfolds to cover the structure in all directions.

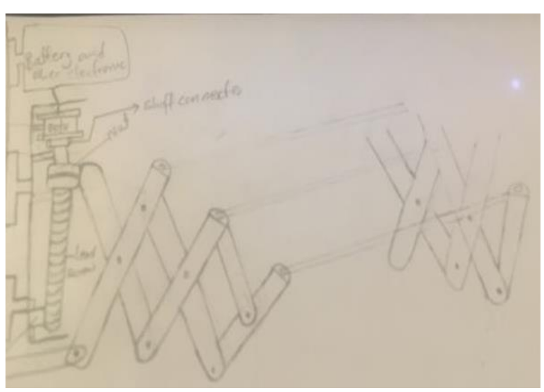


Figure 3.2: Hand sketch of concept 2

Design concept 3: Wall mounted conveyor drying line

The wall mounted conveyor drying line (Figure 3.3) is a stationary rectangular wall mounted frame with hanging lines on a conveyor tray. The conveyor tray with hanging clothes moves in and out of the rectangular frame based on the prevailing weather. When raining or the environment is humid, the conveyor tray moves inwards to get covered by the rectangular frame. When it stops raining, the conveyor tray with hanging clothes moves outwards to get exposed to the sunlight.

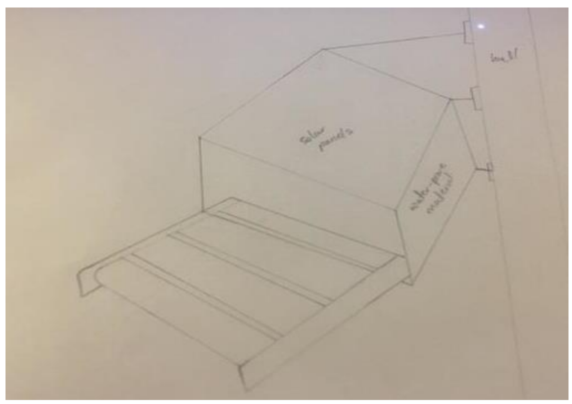


Figure 3.3: Hand sketch of concept 3

3.3 Frame Design Selection Matrix (Pugh Matrix)

The Pugh Matrix below (Table 3.1) shows the selection of the best design from the three proposed design concepts. The Pugh Matrix used the common or traditional drying line as a reference and the set evaluation criteria to select the best design. Availability and cost of materials or components, the first set criteria for the design, are evaluated in the material selection section 4.1. Hence, they are not included in this Pugh Matrix.

On the Pugh Matrix, the three frame design concepts were evaluated on simplicity, ease of use, durability, and size. The “sum +’s” on the Pugh Matrix represents the summation of the positive values on a column, the “sum – ‘s” represents the summation of the negative values on a column and the “sum 0’s” represents the summation of the zeros on a column. The “net score” calculates the net values on a column. The row “Rank” positions the concepts based on the net scores.

Table 3.1: Design selection

Evaluation Criteria	Concept 1	Concept 2	Common Drying Line	Concept 3
Simplicity	-1	-1	0	-1
User Friendly	+1	+1	0	+1
Durability	+1	+1	0	-1
Size	-1	+1	0	-1
Sum +’s	2	3	0	1
Sum 0’s	0	0	3	0
Sum – ‘s	2	1	0	3
Net score	0	2	0	-2
Rank	2	1	2	3

From (Table 3.1), the traditional drying line is simpler than all the three design concepts. However, all three design concepts are easier to use, durable and occupy less space compare to the traditional drying line. Concept 3 (Figure 3.3) is less durable because the case attached to the wall has more load concentrated at one end, which can cause easy failure on the structure. In addition, concept 1 and 2 (Figure 3.1 & Figure 3.2) are more durable and user-friendly but design concept 1 (Figure 3.1) occupies more space. Therefore, design concept 2 (Figure 3.2) is the chosen frame for this design since it satisfies all set criteria.

3.4 Working Principle of the Chosen Design

The automatic retractable clothes drying rack is divided into four different parts: The clothes drying rack frame, the linear actuator, the sensors and electronics, and the cover curtain. This section discussed the different parts of the system in detail.

3.4.1 The Frame and Hanging Rods

The frame or structure of the system is a well machined seesaw-like mechanism that facilitates the retraction and retrieval of the clothes based on the weather conditions of the environment. Each flat bar is 20 cm $\times$ 4 cm $\times$ 1 cm with a pivot bolt of 3 cm long and 1 cm diameter connecting the bars. The drying rack has three hanging rods 60cm long and each can withstand a maximum weight of three medium jean trousers.

Appendix 1 contains a complete engineering drawing of all parts of the frame with dimensions.

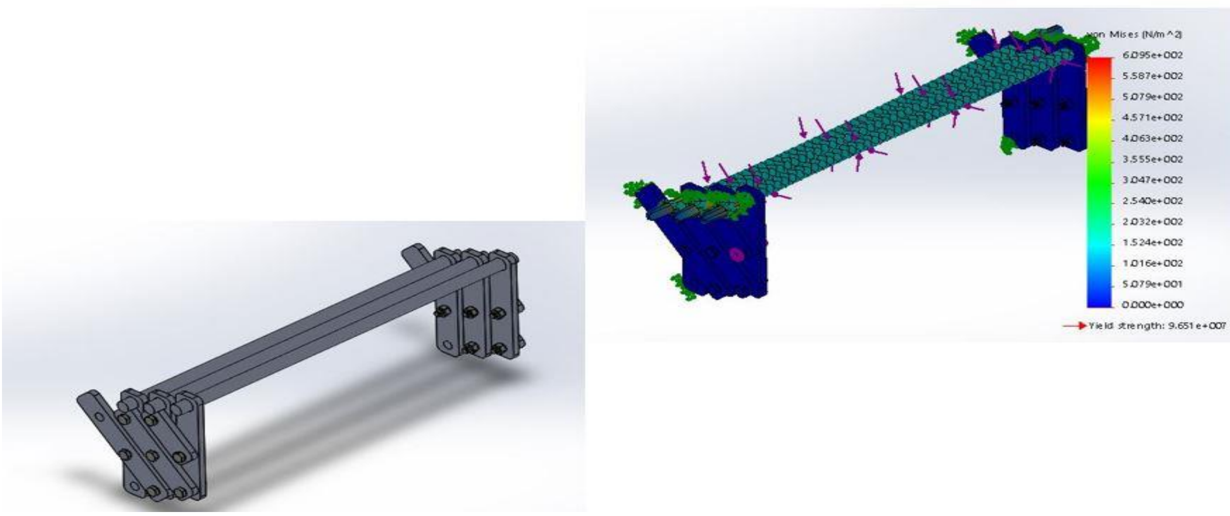


Figure 3.4: Solid works design and simulation of retractable clothes drying rack

3.4.2 Linear Motion Mechanism of the Frame

The frame for the system must move linearly, front and back. This is done using a linear motion mechanism (linear actuator). Linear actuators (Figure 3.6) can be mechanical actuators, hydraulic actuators, pneumatic actuators, electro-mechanical actuators, piezoelectric actuators or twisted and coiled polymers actuators. However, an electro-mechanical actuator which uses an electric motor is the common linear actuator used in electro-mechanical industries and it is most preferable for this design [8].

Electro-mechanical actuators offer the strength of hydraulic and Mechanical actuators but with more precise movement and motion control [9]. In an electro-mechanical actuator, an electric motor is mechanically connected to a leadscrew using a coupler. The coupler can be attached with a coupling assembly, counterbore pressed fit or hollow shaft pressed fit. However, these devices do not allow easy dismantling during maintenance. Although there are other coupling devices like the Thomson taper lock which is highly accurate, easy to assemble and occupies less space, they are not readily available and are costly [10]. Therefore, the suitable coupler for this design is the coupling assembly because cost and availability are key in this project.

After connecting the motor to the leadscrew using the coupler, the rotational motion of the motor will be translated to a linear motion by the leadscrew with a nut. Leadscrews are programmable and it has a low operation cost [8]. The leadscrew and the nut for this project are built for high torque and moderate speed. The threads on the leadscrew facilitate the linear movement of the nut along the screw as the leadscrew rotates with the electric motor.

An electric motor is a device that converts electrical energy into mechanical energy. All motors, whether AC or DC, have a similar mode of operation because they all generate an output torque to drive a load. However, there is a perfect motor match based on each application.

This project requires high torque, cheap, easily available and accurate electric motor. The motor must be well suited for a linear application, but also must have an efficient torque to speed ratio, a simple drive architecture and be affordable. To achieve the linear application perfectly, linear motors can be used because they provide correct positioning and are accurate but they are very expensive and complex compared to rotary motors [11].

From the literature, the rotatory motors commonly used for linear motion applications are the DC stepper motor, the DC brush servo motor and the DC brushless servo motor [12]. DC stepper motor has a simple signal needed for rotation and is inexpensive. However, torque drops drastically at high speed. Although the brushless DC Servo motor has a better speed to torque ratio than the DC stepper motor, it has a higher drive complexity and is expensive. Interestingly, the DC Brush Servo motor has a better speed to torque ratio than the DC stepper motor, is also inexpensive and has a simple drive. However, the response time for the DC Brush Servo motor is low and brushes can wear out [11]. Therefore, since volume is not important in this design and the drying line need not move at a very high speed, the DC stepper motor will be the best to use.

The research revealed that the output torque and power for a DC stepper motor depend significantly on the motor driver used [13]. Stepper motor requires high voltage and to efficiently control the current, stable operation and higher torque DC stepper motor drive must be used. The DC stepper motor drive controls how the stepper motor operates by sending pulses as an input to the stepper motor [14]. The A4988 and DM542 stepper motor drives are the best drive options for this project because they are cheap and easily available.

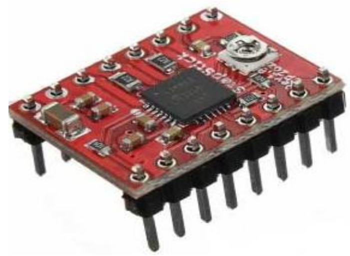


Figure 3.5: A4988 motor controller

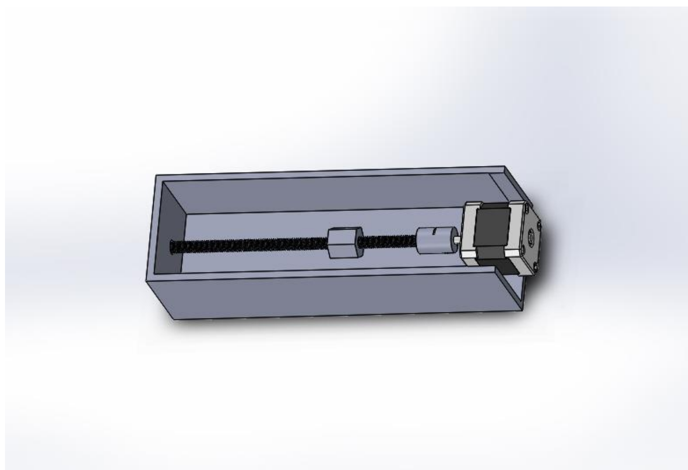


Figure 3.6: Solid works design of the linear actuator

3.4.3 Sensors and Control

A sensor is a device that receives a stimulus and responds with an electrical signal [15]. The sensors for this project will receive sunshine, rainfall, and humidity as stimuli and then respond with an electrical signal that triggers the system to do work (i.e. retracting and releasing the clothes). This project used the Light Dependent Resistor (LDR), a humidity sensor (DHT11) and a water sensor. These sensors are controlled by a programmed microcontroller on an Arduino Uno to perform the needed operation for the automatic retractable clothes drying rack.

The Light Dependent Resistor (LDR) or photoresistor (Figure 3.7) senses the sunlight intensity in the environment. LDRs are made up of semiconductors and the resistance of the LDR decreases as light is imposed on it. The resistance of the LDR can be up to 10 MΩ (100 lux) when the surrounding is dark [16]. The relationship between illumination and resistance was used to program the LDR.

Figure 3.7: LDR

Humidity sensors sense and measure the amount of moisture present in the atmosphere. Based on the unit of measurement, humidity sensors are grouped into two main classes: Relative Humidity and Absolute Humidity. The Relative Humidity measurements are preferable because they are generally simpler and have various applications.

Humidity sensors can also be classified into thermal conductivity humidity sensors, resistive humidity sensors or capacitive humidity sensors based on the mode of operation. The thermal conductivity humidity sensor measures Absolute Humidity. The resistive humidity sensors measure the humidity and relate it to the impedance of the medium. However, the resistive humidity sensor is sensitive to chemical vapors and other contaminants. For the capacitive humidity sensor, the electric permeability of the dielectric material changes with a change in humidity. Capacitive humidity sensors are accurate [17]. The capacitive humidity DHT22 sensor is used for this project because it is cheap, accurate and easily available.

Figure 3.8: DHT22 temperature and humidity sensor

The water sensor senses and measures rainfall intensity. The water sensor (Figure 3.9) requires a 5V DC source and its Light Emitting Diode (LED) remains on when there are no water droplets on the induction board. When the little amount of water drops, the switch indicator (LED) turns off and the digital output becomes low. The droplets of rainwater received by the rain sensor are sent as a signal to the microprocessor for processing. The accumulative raindrops also change the capacitive of the sensor [18].

Figure 3.9: The water drop sensor

A microprocessor is a multipurpose, programmable, silicon microchip. It uses digital data as input and then processes the data according to instructions stored in its memory to give an output [19]. The microprocessor has a mounted microcontroller and it receives signals from the LDR, the humidity sensor, the rain detector, and the motors.

From the literature review, the three most commonly used microcontrollers for the Arduino microprocessor in similar projects include PIC16F877A, ATmega328P, ATmega8A, and AT89C52. All these microcontrollers are efficient and cheap. This project worked with ATmega328p because it was readily available.

A 12V power system is designed to supply power to the sensors, microcontrollers and the two stepper motors.

3.4.4 Proteus Schematic of the Control Circuit

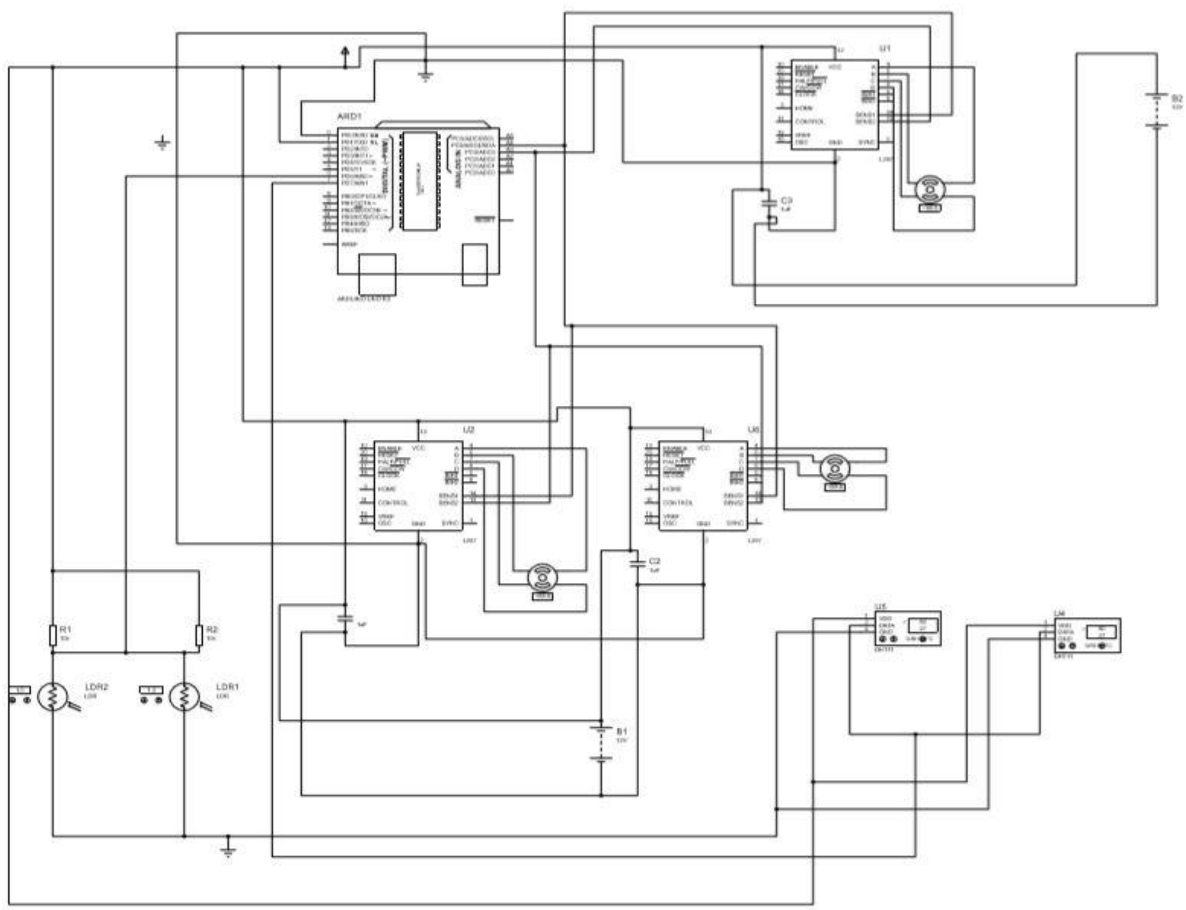


Figure 3.10: Schematic of the design

3.4.5 Cover Curtain Mechanism

The cover curtain is used to cover up the clothes after retrieval. The material selected for this design is a soft fabric Polyvinyl Chloride (PVC). This is the cheapest, versatile and widely used polymer. PVC can be in both rigid and soft form based on the application it will be used for. Its density ranges between 1300 to 1580 kg/m^3 and Young's Modulus of 4140 MPa [20]. This material is folded on a rod and the rod is rotated by a stepper motor with spur gears to increase the torque. The design of the cover curtain is dependent on the output of the sensors and the stepper motors controlling the movement of the drying rack frame. The motor rotates clockwise or counterclockwise to pull the curtain up or down, based on the weather conditions of the surrounding.

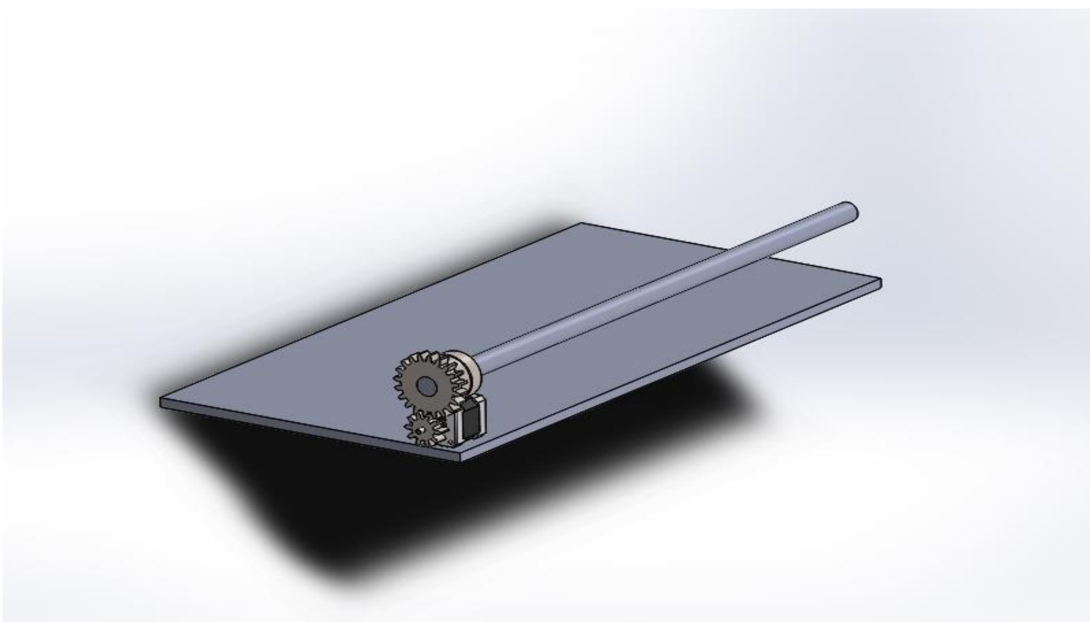


Figure 3.11: Solid works design of cover curtain

3.5 Block Diagram of the Design

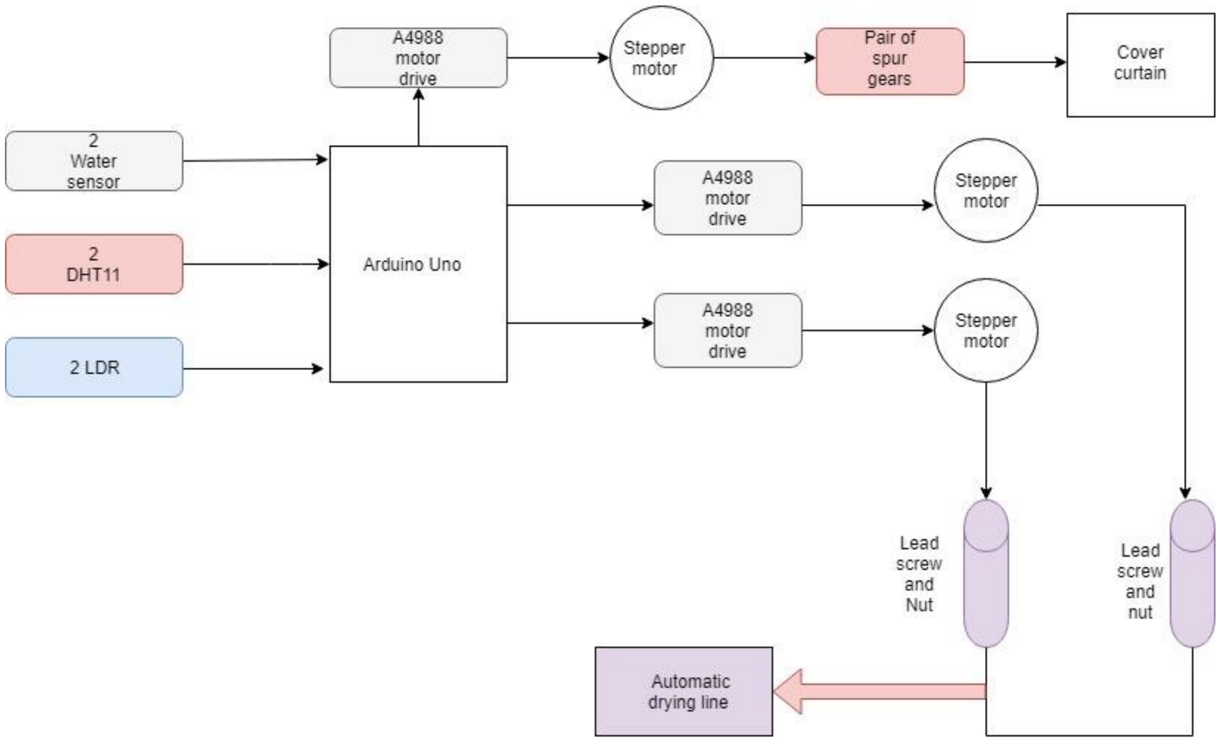


Figure 3.12: Flow chart showing the framework of design

Chapter 4: Methodology 2 - Mathematical Modeling

This chapter discussed the criteria for material selection and as well shows the milestones taken in selecting the material for the system. The chapter also detailed out the mathematical modeling of the hanging rod, the stress analysis and factor of safety calculation for the design, the leadscrew and motor selection approach, and the cover curtain modeling.

4.1 Material Selection: Cambridge Engineering Selector

Cambridge Engineering Selector (CES) is an engineering software package used for material selection. It has a large database of materials, manufacturing processes, and shapes for about 3000 engineering materials [21]. The software is easy to install and use.

4.1.1 Criteria for Material Selection

The CES software requires the input of some criteria to effectively carry out the material selection. The selected criteria for the system were geared towards generating the best material for the frame and the hanging rods.

The Young's Modulus (E) and Density (ρ)

The Young's Modulus describes the elastic property of a solid undergoing compression or tension. The Young's Modulus is defined by Hook's Law as $E = \frac{\sigma}{\varepsilon}$. Where σ is the stress on the material and ε is the elongation on the material due to apply load [22]. The density of a material is the mass per unit volume of the material.

In this design, the Specific Modulus, which is the ratio of the Young's Modulus to the density is very key. This ratio is considered to minimize the weight of the device. A part made with a high Specific Modulus will have low deflection, high stiffness, and high natural frequency[23]. Therefore, a high Specific Modulus is an important design criterion for the automatic retractable clothes drying rack.

Fracture Toughness and Fatigue Stress

Fracture toughness is a measure of a material resistant to the extension of a crack [24]. It is directly proportional to the Young's Modulus of the material. The fabricated drying rack will be exposed to stresses from both the environment and the hanging clothes. Hence, the material needs to be strong to withstand stress without fracturing.

Fatigue stress/strength is the progressive structural damage when the material is exposed to cyclic loading [23]. Fatigue of the material can be determined by the endurance limit of the material and the stress concentration. For this system, the fatigue cycle can either be high or zero because clothes are either hanged or not hanged. However, this design is interested in high fatigue stress/strength and high fracture toughness.

Availability and Cost of Material

The selected material must be available in the market at a very cheap price to meet the objective of the design. A price range of $1.9 /kg to $2.5/kg is considered cheap for this design.

In addition, the material must be environmentally friendly (high corrosion resistance) and machinable.

4.1.2 Load Analysis of the Design

Under the load analysis of the design, the density and the Young’s Modulus of the material, and the moment diagram of the hanging rod with distributed loads were analyzed. One hanging rod (0.6 m long) was used in these calculations. Each hanging rod should withstand a weight of at least three different wet clothes. The three wet clothes chosen for this design were a wet towel, a wet pair of jeans and a wet cotton dress with their respective weights (Table 4.1) [25]. Since the clothes will not be always uniformly distributed on the hanging rod as shown in Figure 4.1, the analysis will be simplified by taking the maximum total load and assuming it is applied at the center of the rod.

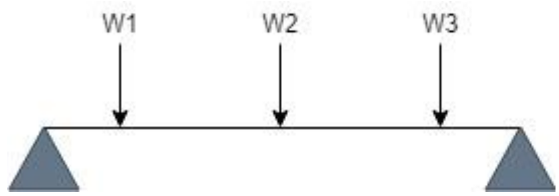


Figure 4.1: Distributed load on hanging rod

Table 4.1: Weight of selected wet clothes

Wet Clothes	Mass (Kg)	Weight (N)
Towel	0.75	7.35
Jean	0.7	6.86
Cotton Dress	0.15	1.47

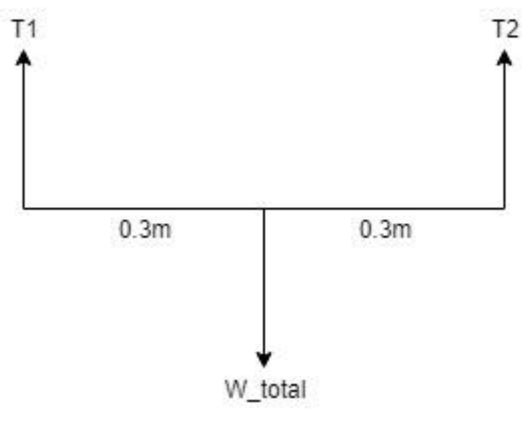


Figure 4.2: Concentrated force balance on the hanging rod

Resolution of Forces

$$W_{total} = 7.35 + 6.86 + 1.47$$

$$W_{total} = 15.68N$$

Applying the equilibrium equation of the sum of forces $\sum F_y = 0$

$$T_1 + T_2 - W_{total} = 0$$

$$T_1 + T_2 = W_{total}$$

$$T_1 + T_2 = 15.68 \text{ N}$$

$$T_1 = 15.68 - T_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 1}$$

Applying the equilibrium equation of sum of the moment about a point $\sum M_A = 0$

$$0.3 \times W_{total} - 0.6T_2 = 0$$

$$0.3 \times (15.68) = 0.6T_2$$

$$T_2 = 7.84 \text{ N}$$

Substituting T_2 into Eq. 1

$$T_1 = 15.68 - 7.84 \text{ N}$$

$$T_1 = 7.84 \text{ N}$$

T_1 and T_2 are the reaction forces.

This design works within the elastic region. The maximum applied force on the drying rack (F_{max}) is used to calculate the yield strength of the material. Assuming the clothes hangers or pegs to be massless. The maximum and minimum applied force on each hanging rod is:

$$F_{max} = 15.68 \text{ N}$$

$$F_{min} = 1.47 \times 3 = 4.41 \text{ N}$$

Calculating Young's Modules (E)

The hanging rod for this design is 0.6 m long with a radius (r) of 0.01 m. Therefore, its area is:

$$A = \pi r^2$$

$$= \pi \times 0.01^2$$

$$= 0.000314 \text{ m}^2$$

The elongation of the material Δl depends on the brittleness and ductility of the material. For this project, a percentage elongation (%E) of slightly greater than 5% is used since the material is to be slightly ductile to avoid shear failure. Therefore, the elongation is

$$\frac{\Delta l}{l_o} = \%E$$

$$\Delta l = l_o \times \%E$$

Let the %E be 0.052

$$\Delta l = 0.6 \text{ m} \times 0.052$$

$$\Delta l = 0.0312 \text{ m}$$

$$E = \frac{Stress}{Strain} = \frac{F_{max} l_o}{\Delta l \; A}$$

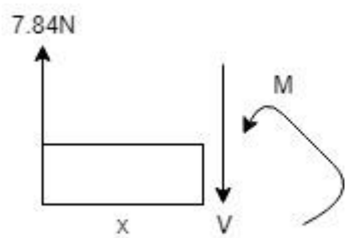
$$E = \frac{15.68 \text{ N} \times 0.6 \text{ m}}{0.000314 \text{ m}^2 \times 0.0312 \text{ m}}$$

$$E = 0.9603 \text{ MPa}$$

The Young's modulus of the material for the design can be any value greater than or equal to 0.9603 MPa.

Bending Moment Diagram

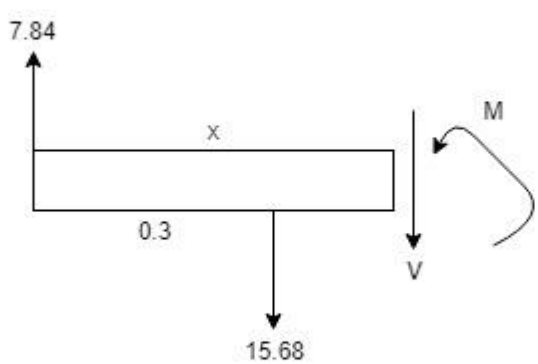
$$0 \leq x \leq 0.3$$



$$\sum M = 0$$

$$7.84x - M = 0$$

$$M = 7.84x$$



$$0 \leq x \leq 0.6$$

$$\sum M = 0$$

$$7.84x - 15.86\,(x - 0.3) - M = 0$$

$$7.84x - 15.68x + 4.758 - M = 0$$

$$M = -7.84x + 4.758$$

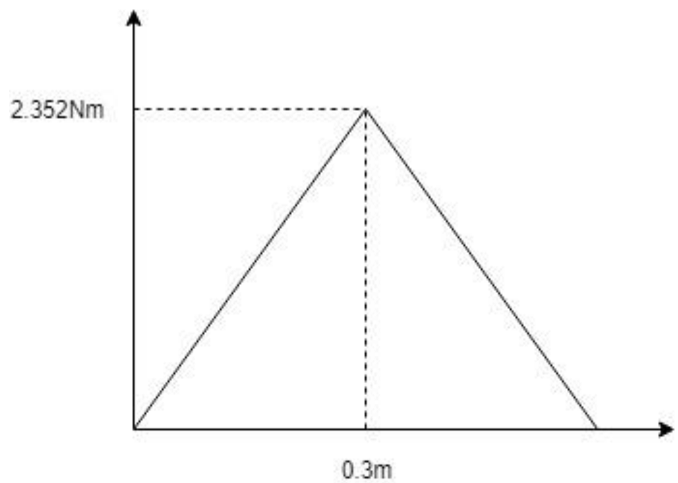


Figure 4.3: Bending moment diagram

Calculating the Density of the Material

Mass on one hanger rod is $0.75\ \text{kg} + 0.7\ \text{kg} + 0.15\ \text{kg} = 1.6\ \text{kg}$

The volume of one hanger rod is:

$$\text{Volume} = 0.000314\ \text{m}^2 \times 0.6\ \text{m}$$

$$= 1.884 \times 10^{-4}\ \text{m}^3$$

$$\text{Therefore, density} = \frac{1.6\ \text{kg}}{1.884\ \times\ 10^{-4}\ \text{m}^3} = 8492.57\frac{\text{kg}}{\text{m}^3}$$

$$= 8.49\ \text{g/cm}^3$$

The density of the material can be any value less than or equal to $8.49\ \text{g/cm}^3$. From research, metals and ceramics have been the commonly used materials in clothes rack designs because they fall within the range of medium to high density and their Young's Modulus is high. Polymers have a low density which can easily cause material failure.

4.1.3 Material Selection Chart

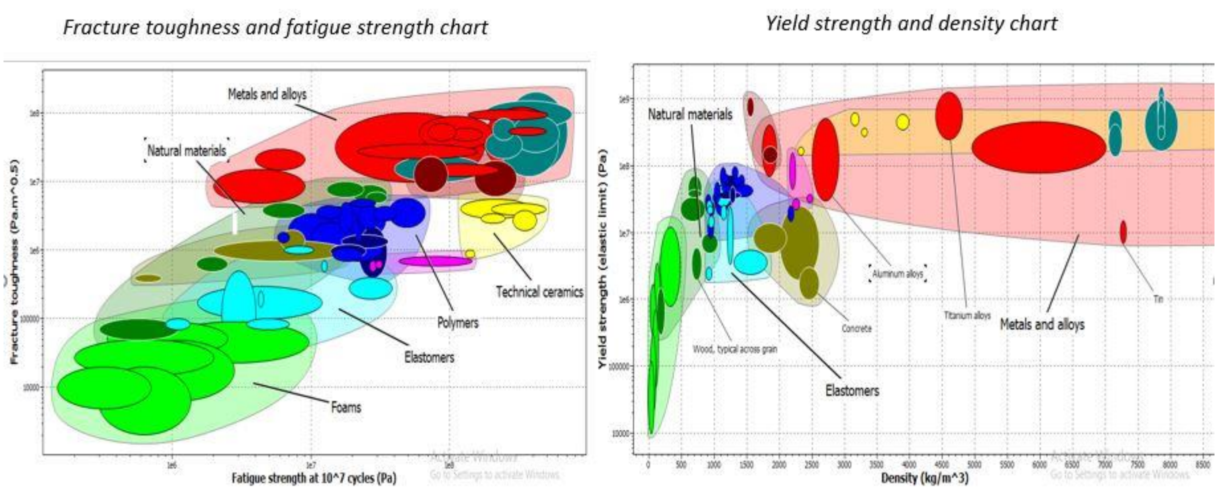


Figure 4.4: CES generated charts

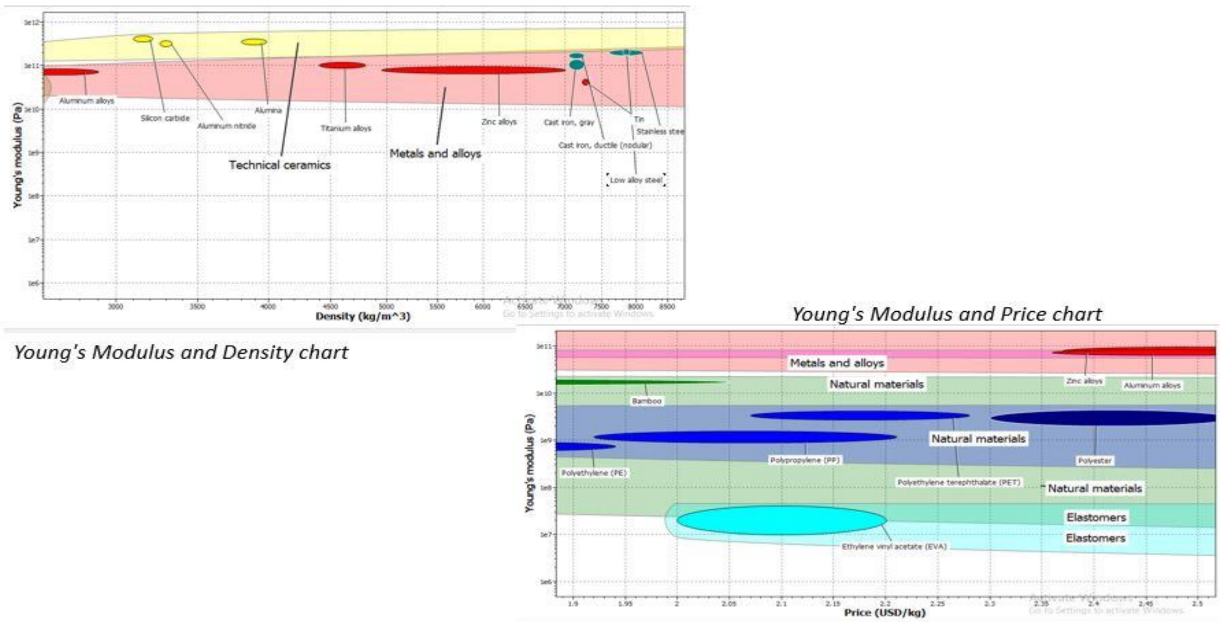


Figure 4.5: CES generated charts

From the above graphs (Figure 4.4 & 4.5), metals, and alloys (aluminum alloy, low alloy steel), ceramics and natural materials /polymers (bamboo) fall within the design specification.

Table 4.2: Selecting the best material for the design

Material/Criteria	Fracture Toughness	Price	Young's Modulus	Fatigue Strength	Density
Metals and Alloys	High	Average	High	High	High
Ceramics	Medium	Expensive	Very High	High	Medium
Natural Material/polymers	Medium	Cheap	Low	Low	Low

From table 4.2, metal and alloys and natural material/polymers will be the perfect materials for the drying rack frame and hanging rods.

4.1.4 Research on some Possible Materials for the Drying Rack Frame

Low Carbon Steel

Carbon steel is an alloy of mainly iron and carbon and a few additions of other elements like silicon, copper, and manganese. Low carbon is cheap and easy to shape. It is a good balance for toughness, strength, and ductility. In addition, it has good machining properties and Brinell hardness. AISI 1018 low carbon steel has 78% machinability, 370MPa, and 440MPa ultimate tensile strength and yield strength respectively, and 145MPa hardness[26]. Carbon AISI 1212 has a yield strength of 415MPa and tensile strength of 540MPa. It machinability is 100% [27]. Low Carbon Steels are used for fixtures as well, but they have low corrosion resistance.

Aluminum Alloys

Aluminum Alloy is a composition of pure Aluminum and other chemicals elements to improve its properties, mainly its strength. These elements include Iron, Copper, Magnesium, Silicon, Manganese, and Zinc. Aluminum-Magnesium (Al-Mg) Alloys is highly available. It can be in different forms such as plate, bar, sheet, strip, power, foil. This alloy has a density of 1.9 g/cm^3 and tensile strength of 230 to 280 MPa (Ultimate) / 130 to 180 MPa (yield). This material has good properties like good machinability, medium density, and high strength. The tensile strength and yield strength of Al-Mg increases as the percentage of magnesium increases in the alloy but the elongation decreases [28].

Bamboo

Bamboo has a high strength to weight ratio and is known as natural glass fiber. Bamboo is an attractive alternative to steel in a tensile loading application because of its high tensile strength of 370 MPa [29]. The shrinkage of bamboo differs with the moisture content. The compression stress and Young's Modules of bamboo depend on the age of the bamboo. The older the bamboo the stronger it is. The density is about $600\ \mathrm{kg/m^3}$ [30]. Bamboo has about 35% of water absorption when soaked in water for 24 hours. During summer, bamboo has 6.92% of moisture content [31].

From this analysis, bamboo and Aluminum-Magnesium Alloy are the feasible materials for this design. However, with the low Young's Modulus and low fracture toughness of bamboo, Aluminum Magnesium Alloy is preferable.

4.1.5 Stress Analysis of the Frame

Considering the loading type which is repeating loading on the hanging rods, the stress on each haging rod was designed to be either zero or maximum. This stress is mainly bending stress.

Midrange and Amplitude Bending Stresses

$$\mathrm{M_{mean}} = \frac{\mathrm{M_{max}} + \mathrm{M_{min}}}{2} = \frac{2.352 + 0}{2} = 1.176\mathrm{Nm}$$

$$\mathrm{M_a} = \frac{\mathrm{M_{max}} - \mathrm{M_{min}}}{2} = \frac{2.352 - 0}{2} = 1.176\mathrm{Nm}$$

$$\sigma_{\mathrm{mean}} = \frac{32 * \mathrm{M_{mean}}}{\pi \mathrm{d}^3} = \frac{32 * 1.176}{\pi * (0.02)^3} = 1.497\mathrm{MPa}$$

$$\sigma_{\mathrm{a}} = \frac{32 * \mathrm{M_a}}{\pi \mathrm{d}^3} = 1.497\mathrm{MPa}$$

Since $\mathrm{M_{mean}} = \mathrm{M_a}$, σ_{mean} will also be equal to σ_a .

The Factor of Safety Calculation

The factor of safety due to fatigue can be determined using Goodman criteria for fatigue calculation equation.

$$n_f = \frac{S_y}{\sigma_{mean} + \sigma_a}$$

$$n_f = \frac{130 \text{ MPa}}{1.497 \text{ MPa} + 1.497 \text{ MPa}}$$

$$n_f = 43.4$$

The high factor of safety implies that heavier clothes than the designed weight can we hang on the drying rack without it failing. However, it indicates material wastage and hence, will increase the cost of the device.

4.1.6 Bolts Selection – Material and Size

Pivot bolt and nut are needed to connect the flat bars for the drying rack. From section 4.1, the minimum yield strength of 50 kPa and a minimum tensile strength of 66.39 kPa will act on each of the three-hanging rods. The pivot bolts on each side of the drying line supporting the flat bars will equally share the load. The proof load for each bolt is 8 N to 11 N. To select the bolt for the drying line frame, American Society for Testing and Material (ASTM) specification was used. The ASTM bolt specification has shorter threaded bolts because it deals with structural connections which are generally loaded in shear[32]. The grade of the bolt selected is the same as the grade for the nut. From table 8-10 of Shigley's Mechanical Engineering Design by Richard and Keith, an A307 Low Carbon bolt of diameter 0.6cm - 3.8cm bolt is perfect for this design.

4.2 Mathematical Modeling for Leadscrew and Motor Sizing

The leadscrew for the linear motion mechanism was sized with the correct dimensions and parameters in order to effectively fit into the system design. A correct stepper motor with efficient torque to overcome the load on the clothes drying rack was selected as well. This section entails the leadscrew sizing and stepper motor selection.

The Total Mass of the Retractable Clothes Drying Rack

The estimated total weight of the whole system is the weight of the frame and the weight of the hanging clothes. The maximum weight ($\mathrm{F_{max}}$) of the hanging clothes on one hanging rod is 15.68 N. The total weight of the clothes on the three hanging rods is:

$$F_{total} = 15.68\mathrm{N} \times 3$$

$$= 47.04\ \mathrm{N}$$

The total mass on the three hanging rods due to the clothes m_{totalC}

$$m_{totalC} = \frac{47.04\mathrm{N}}{9.8\ \mathrm{m/s^2}}$$

$$= 4.8\ \mathrm{kg}$$

The density of Aluminum-Magnesium Alloy is 1900 $\mathrm{kg/m^3}$. Assuming the volume of each of the twelve frame-bars is $8 \times 10^{-5}\ \mathrm{m^3}$ and the volume of each hanging rod is $1.885 \times 10^{-4}\ \mathrm{m^3}$. The total volume of the frame ($\mathrm{V_{totalF}}$) is

$$\mathrm{V_{totalF}} = (12 \times 8 \times 10^{-5}) + (3 \times 1.885 \times 10^{-4}\ \mathrm{m^3})$$

$$\mathrm{V_{totalF}} = 0.0015255\ \mathrm{m^3}$$

Therefore, the total mass of the frame is

$$m_{totalF} = V_{totalF} \times 1900 \text{ kg/m}^3$$

$$m_{totalF} = 0.0015255 \text{ m}^3 \times 1900 \frac{\text{kg}}{\text{m}^3}$$

$$= 2.89845 \text{ kg}$$

$$m_{total} = 2.89845 \text{ kg} + 4.8 \text{ kg}$$

$$= 7.6985 \text{ kg}$$

$$W_{total} = 7.69855 \text{ kg} \times 9.8 \frac{\text{m}}{\text{s}^2}$$

$$= 75.44 \text{ N}$$

Therefore, the total load to be overcome by the electric motor is 75.44 N.

The sizing of the lead screw and motor is done using machine design concepts [11].

Table 4.3: Estimated design parameters

Mass of the system (m_{total})	9.19845 kg
Estimated maximum linear Move Distance (d)	0.3 m
Estimated moved time (t)	60 s
Estimated lead screw dimension	0.20 m long, 0.015 m diameter

Power Needed to Move the Load

$$P = \frac{F \times d}{t}$$

$$P = \frac{7.6985 \text{ kg} \times 9.8 \frac{\text{m}}{\text{s}^2} \times 0.3 \text{ m}}{60 \text{ s}}$$

$$P = 0.3772 \text{ W}$$

The Peak Linear Velocity of the System

$$V_{pk} = \frac{3d}{2t}$$

$$V_{pk} = \frac{3 \times 0.3 \text{ m}}{2 \times 60 \text{ s}}$$

$$V_{pk} = 0.0075 \ \frac{\text{m}}{\text{s}}$$

The Maximum Screw Lead

$$L = \frac{V_{pk} \times 60}{\text{Estimated Screw RPM}}$$

$$L = \frac{0.0075 \ \frac{\text{m}}{\text{s}} \times 60}{1000 \text{ RPM}}$$

$$L = 0.00045 \text{ m}$$

$$= 0.45 \text{ mm}$$

From the above calculations, the leadscrew specification of this project is a 0.2 m long, 0.015 m diameter, 0.45 mm pitch.

The Shaft Torque of the Leadscrew

This shaft torque can be obtained from the torque due to friction, the torque due to gravity and the torque due to the external force.

$$T = T_f + T_g + T_{ext}$$

$$T_f = \frac{\text{Cos}\theta \times mg \times \mu \times L}{2\pi n_s}$$

$$T_g = \frac{\sin\theta \times mg \times L}{2\pi n_s}$$

$$T_{ext} = J_T \times \alpha$$

J_t is the total inertia to be connected to the motor. And it depends on the load inertia (J_L) and the screw lead inertia (J_s).

$$J_L = M_{TOTAL} \times \left(\frac{L}{2\pi}\right)^2$$

$$J_L = 7.6985 \text{ kg} \left(\frac{0.00045 \text{ m}}{2\pi}\right)^2$$

$$J_L = 3.9489 \times 10^{-8} \text{ kgm}^2$$

The screw lead inertia J_s can be neglected because its value is insignificant.

$$J_T = J_L$$

The angular acceleration of the system

$$\alpha = \frac{2\pi a}{L}$$

$$a = \frac{v_f - v_i}{t_f - t_i}$$

$$a = \frac{0.0075 \frac{m}{s} - 0 \frac{m}{s}}{60 \text{ s} - 0 \text{ s}}$$

$$a = 0.000125 \text{ m/s}^2$$

$$\alpha = \frac{2\pi \times 0.000125 \text{ m/s}^2}{0.00045 \text{ m}}$$

$$\alpha = 1.7453 \text{ rad/s}^2$$

$$T = T_f + T_g + T_{ext}$$

$T = (\frac{\cos\theta \times mg \times \mu \times L}{2\pi n_s}) + (\frac{\sin\theta \times mg \times L}{2\pi n_s}) + (J_T \times \alpha)$ where n_s is the estimated efficiency of the system and μ is the coefficient of friction. The coefficient of friction between the dry aluminum plate is1.05– 1.35.

$$T = (\frac{\cos 90 \times 7.6985 \text{ kg} \times 9.8 \frac{m}{s^2} \times 1.35 \times 0.00045 \text{ m}}{2\pi \times 0.9}) + (\frac{\sin 90 \times 7.6985 \text{ kg} \times 9.8 \frac{m}{s^2} \times 0.00045 \text{ m}}{2\pi \times 0.9}) +$$

$$(3.9489 \times 10^{-8} \text{ kgm}^2 \times 1.7453 \text{ rad/s}^2)$$

$$T = 0.006 \text{ Nm}$$

Power Required to Drive the Leadscrew Shaft / Power Output of the Motor

$$\text{Power}_{pk\ (MotorOutput)} = T \times W_{pk}$$

$$\text{Power}_{pk\ (MotorOutput)} = 0.006\text{Nm} \times 104.733 \text{ rad/s}$$

$$\text{Power}_{pk\ (MotorOutput)} = 0.6284 \text{ W}$$

Therefore, the electric motor for this project should have an output power of at least 0.6284W and a shaft torque of 0.006Nm.

4.3 Mathematical Modeling of Cover Curtain Mechanism

The stepper motor for the design of the cover curtain must roll the curtain up or down based on the weather condition. This stepper motor will be connected to a shaft by spur gears as shown in Figure 3.11. The output torque of the stepper motor needed to overcome the weight of the PVC shaft is:

$$F = ma$$

F = (mass of a 0.6m of PVC pipe + mass of a meter of PVC fabric) × (acceleration due to gravity)

Mass of PVC pipe = Volume × density

$$V = \pi r^2 \times h$$

$$= \pi \times 0.01^2 \times 0.6 \text{ m}$$

$$= 0.000188 \text{ m}^3$$

Therefore, the mass of PVC pipe is:

$$= 0.000188 \text{ m}^3 \times 1300 \frac{\text{Kg}}{\text{m}^3} = 0.24492 \text{ kg}$$

The mass of a meter of PVC fabric is 0.24492 kg

$$F = (0.24492 + 0.24492) \times (9.8)$$

$$= 4.80043 \text{ N}$$

$$T = 4.80043\text{N} \times 0.6\text{m}$$

$$= 2.88 \text{ Nm}$$

Since this torque is slightly high, gears will be coupled to the design to produce high torque.

Gears are used to produce high torque. Spur gears are cheap, easy to manufacture, simple, easy to maintain and readily available [33]. The pitch diameter and gear ratio of the spur gears determine the speed and torque limit of the driven shaft. The shaft with the larger driven gear will have a lower speed and high torque than the shaft with the smaller gear [34]. The pair of spur gears used for the cover curtain design must have a gear ratio of 2 and a circular pitch of 1.1.

$$\text{Gear ratio} = \frac{\text{the pitch diameter of the driven gear}}{\text{the pitch diameter of the driver gear}} = \frac{\text{number of teeth of driven}}{\text{number of teeth of driver}}$$

$$\text{Circular pitch} = \frac{\pi \times \text{ diameter of driven}}{\text{number of teeth of driven}} = \frac{\pi \times \text{ diameter of the driver}}{\text{number of teeth of driver}}$$

With the above equations, a 10 teeth driver and 20 teeth driven gear with a diameter of 3.5cm and 7cm respectively were designed. This implies that the output torque of the selected motor will be doubled after connecting the gears.

Chapter 5: Project Implementation

5.1 Frame and Hanging Rods Implementation

The material selected for the flat bars of the drying rack frame was hollow rectangular Aluminum-Magnesium Alloy. However, the material for the flat bars was substituted by a hollow rectangular Aluminum because of time and easy availability. The Aluminum bar was the closest substitute because it has similar properties to the Aluminum-Magnesium Alloy. A tensile test was conducted on the Aluminum hollow flat bar using the Mechanical Testing and Sensing (MTS) machine and this was the result (Figure 5.1). The yield strength of the material is about 120000 MPa and it has a Young's Modulus of 1952.33 MPa.

Figure 5.1: Stress-strain curve

Since the Aluminum hollow flat bar was bought with a specific dimension (290cm × 5cm × 2.5cm), it changed the dimensions designed for the drying line frame (Appendix 1). The long hollow rectangular Aluminum flat bar was cut into the designed length (20cm) using the multi-cutter saw, but the width and thickness were unchanged.

The hanging rods for the frame were designed to be of the same material as the flat bars. However, considering the availability of the material within the project duration, PVC pipes were used. The PVC pipes have good mechanical properties. The used PVC pipes were of the same dimension (60cm long and 2cm in diameter) as the designed Aluminum-Magnesium hanging rod. Epoxy glue was used to connect the PVC pipes to the frame.

Hexagon screws were obtained for the prototype implementation bolts. The material for the screw was low carbon steel and the length fit well. However, the diameter of the screw was slightly different from the actual design. It was 4 mm instead of 10 mm used in the Solid Works design. A driller was used to drill holes on the hollow bars for the seesaw-like mechanism.

Figure 5.2: Built retractable clothes drying rack frame

5.2 Linear Motion Implementation

The project implemented two linear motion actuators (Figure 5.3), working on the same program and with the same mechanism. The leadscrew used in the implementation had a diameter of 8 mm and a pitch of 0.9 mm. This leadscrew diameter and pitch were smaller than the actual design because of the weight of the aluminum flat bars used as well as availability. A nut of the same diameter as the leadscrew could move along the lead screw as the lead screw rotates (Figure 5.3). The rotation of the leadscrew and movement of the nut was made possible by a 12V NEMA 14 bipolar stepper motor. This stepper motor has a holding torque of 0.098 Nm, a 1.5A current, and a holding power of 5W. The A4988 motor drive was used because it was readily available and can provide a voltage up to 35V at 2A current.

The motor was attached to the leadscrew by a 3D printed coupler. This coupler has a diameter of 5mm and 8mm and was fastened well by screws. To achieve an effective linear motion along the leadscrew, there was a need to make the system stable by ensuring both ends of the leadscrew were supported. One end of the leadscrew was supported by the stepper motor with the aid of the motor coupler. To effectively support the other end and achieve a free rotation of the leadscrew as well, a bearing was used. The well-assembled linear motion actuators were cased with aluminum. Aluminum was cut using the shear cuter and jig-saw and it was bent and riveted into a rectangular case.

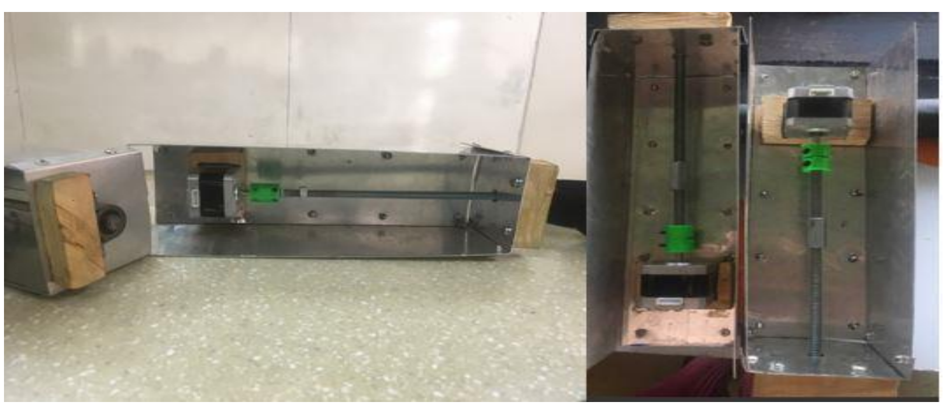


Figure 5.3: Fabricated linear actuator

5.3 Cover Curtain Implementation

The cover curtain was implemented using PVC cloth, a rectangular well-sized wood, stepper motor with A4988 drive, a 70 cm × 30 cm Aluminum plate, a 70 cm long, 2 cm diameter wooden rod, and 3D printed gears with 2:1 velocity ratio.

The driver gear was connected to the stepper motor and the driven gear was connected to the wooden rod. As the stepper motor rotates, it is expected to engage the gears which then rotate the wooden rod. The PVC cloth is wrapped over the wooden rod and based on the direction of rotation of the stepper motor, the curtain is expected to roll up or down. The bearing at the other end of the wooden rod is to facilitate the rotation of the wooden rod.

The cover curtain system was assembled and mounted on the aluminum plate. The aluminum plate is of equal length with the maximum stretch length of the drying line frame.

Figure 5.4: Fabricated cover curtain

5.4 Sensors and Controls Implementation

The sensors and controls were implemented exactly as designed. All the sensors generated in the design were available for implementation. The DHT11, LDR, and water sensor were used. The A4988 motor drive and NEMA 14 stepper motor with Arduino Uno was used to achieve the linear motion control. Below is the diagram of the implemented proteus design. An Arduino code (Appendix 2) was developed to control the rotation of the stepper motors based on the outputs from the sensors. The code allows the motors to rotate in both directions using the step and direction input on the motor drive. An Arduino code was also written separately to test each sensor. After testing both sensors and stepper motor, the code was modified based on the operation of the system. The motor rotates in the counterclockwise direction for 60 steps when there is low humidity, low rainfall, and high light intensity to retrieve the clothes. It as well rotates in the clockwise direction for 60 steps when there is high humidity, rainfall, and low light intensity to retract the clothes.

The cover curtain motor program is synced with the drying rack motor and sensor control. As the system's motors rotate counterclockwise, the cover curtain's motor also rotates counterclockwise to uncover the clothes. The cover curtain only covers up the clothes when there is high humidity, rainfall, and low light intensity.

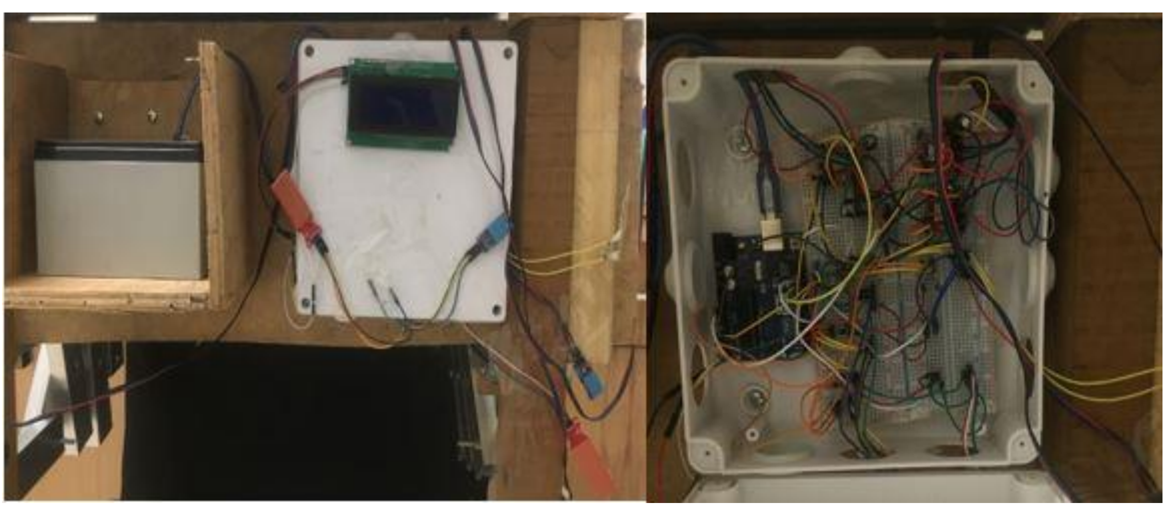


Figure 5.5: Electronic circuit

5.5 Integrating all Components

After building and testing all parts separately, the system was then assembled to test the mechanism of the designed and fabricated system. From the design, the system was supposed to be wall mounted. However, due to certain reasons, the built prototype was assembled on a wooden stand to test and collect data.

The nut on each of the fabricated linear actuators was attached to each of the non-connected upper bars of the frame. As explained in Chapter 3, when the linear actuator is connected, the movement of the nut along the leadscrew should move the drying line frame. The cover curtain is connected a little above the drying rack frame.

Figure 5.6: Assembled automatic retractable clothesline

Chapter 6: Testing, Result, and Analysis

6.1 Testing the Prototype

The built prototype of the design was tested to evaluate its performance. The testing was done in two parts: testing of the integrated parts and testing the system with different weights of hung clothes.

Testing of Integrated Parts

The assembled design was tested with the stepper motors, sensors and cover curtain. This testing was done without clothes hung on the drying line. The aim was to ensure that the system integrates perfectly with all parts.

Testing with Different Clothes

Different loads were suspended on the system to examine the time it takes the system to fully extend and the corresponding length. The clothes drying rack was tested with different clothes and the length of the frame when the clothes were fully released, and the time it took to fully release the clothes were recorded.

These test results were compared with the design values and statistical analysis was done on the values obtained to estimate the relationship between the functionality of the system with the weight of clothes hung. The different clothes in Table 6.1 were used for the test.

Table 6.1: Weight of clothes used in testing

Clothes	Weight (N)
Towel	1.87
Cotton long sleeve	1.46
Cotton long dress	2.75
Cotton top	1.25
Cotton T-shirt	1.48

Testing with 7.321N hanged

System fully released with 8.8N hanged

System being released with 7.312N hanged

System fully retracted with 6.076N hanged

Figure 6.1: Prototype testing

6.2 Result from Testing

Test Result Obtained from Sensors and Cover Curtain

The sensors (DHT11, LDR, and water sensor) correctly read the humidity, sunlight, and rainfall when supplied with a 5V power. The sensor outputs triggered the stepper motors to rotate either clockwise or counterclockwise based on the set control. The system stretched linearly outward when the environment had humidity of below 90%, sunshine with LDR readings below 20 and no rainfall.

The two linear actuators worked as expected. The rotation of the stepper motors caused the leadscrew to rotate. This rotation was translated to a linear motion on the nut, hence, moving the nut vertically along the leadscrew (Figure 5.3). As a result, the clothesline frame moved.

The cover curtain also rotates to cover up the suspended clothes after complete retraction. However, the material for the cover curtain was slightly heavy for the stepper motor, which affected the roll up of the curtain.

Test Result Obtained with Different Clothes

Table 6.2: Result from testing

Cloth weight (N)	Length of the drying rack frame when fully stretched (m)	Time for the drying line to fully stretched (s)
0N	0.220	24.20
6.08	0.240	24.56
7.33	0.245	25.33
8.81	0.235	24.00
1.87	0.226	24.6
2.75	0.230	25.00

6.3 Analysis of the Result

Statistical analysis was done using Statistics Package for the Social Sciences (SPSS) to create a better understanding of the result obtained from testing. A One sample t-test was done using the test variables in Table 6.2. Design variables, length of clothe line when fully stretched and the corresponding time (0.3 m, 60 sec, respectively), were used as the test values in the statistical analysis.

Two different One sample t-test were carried out: Test 1 for the maximum length of the system and Test 2 for the maximum time it took for the system to fully stretch.

For t-test 1, two hypotheses were set (H_o and H_1): where H_o = The sample mean length is equal to the designed mean length and H_1 = The sample mean length is not equal to the designed mean length. Results of the analyses are presented in the table below (Figure 6.2)

T-Test

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
VAR00001	6	.2327	.00920	.00376

One-Sample Test

	Test Value = 0.3					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
VAR00001	-17.925	5	.000	-.06733	-.0770	-.0577

Figure 6.2: Result from T-Test 1

From Figure 6.2, the p-value (Sig. (2-tailed) is less than 0.001 and from a statistical point of view, this implies that the null hypothesis that the sample mean length is equal to the designed mean length is rejected. From the mean difference obtained in the t-test, the mean prototype length is about 0.0733 m less than the designed mean length of the automatic retractable clothes drying rack.

The deviation between the results obtained from the prototype analysis and the design values were expected since the prototype was not built to scale of the design. However, obtained results from the basic analysis point in the right direction to the functionality of the designed product.

For t-test 2, the two set hypotheses were: H_o = The sample mean time is equal to the designed mean time and H_1 = The sample mean time is not equal to the designed mean time

T-Test

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
VAR00003	6	24.6150	.49257	.20109

One-Sample Test

	Test Value = 60					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
VAR00003	-175.963	5	.000	-35.38500	-35.9019	-34.8681

Figure 6.3: Result from T-Test 2

Figure 6.3 shows a p-value (Sig. (2-tailed) less than 0.001, hence, the null hypothesis that the sample mean time is equal to the designed mean time is rejected. From the mean difference obtained in the t-test, the built prototype released the hung clothes faster than the designed time.

Again, this was expected because the prototype was not built to scale. The 60 s obtained from the design was specific to a designed weight of about 50N. The testing was done with lesser clothes. Therefore, the result from the test shows a correct functionality of the system, the clothes rack operates faster when lesser loads are suspended.

Chapter 7: Conclusion, Limitations and Future Work

7.1 Conclusion

The results from the tests have shown that the automatic retractable clothes drying rack worked as expected, it retrieved and released the clothes based on the set parameters. As more clothes are hung on the system, the speed while retrieving and releasing the clothes decreases and thus prolong the time taken for the frame to complete its linear motion. Also, stretch distance for the designed and built frame increases as the load on the system gets heavier. The heavy load exerted tends to pull the joints of the seesaw-like mechanism frame and this forces the frame to be completely stretched but at a slower rate. However, all these phenomena can only be noticed when there is a significant change in the weight of the hung clothes.

Therefore, referring to the objectives of the project, one can strongly argue that 95% of the set objectives were all met. The designed and built system was fully implemented in West Africa (Ghana) and it helps in facilitating the drying of clothes in highly humid and rainy environments. This system is cheap as well because it cost roughly GHC 200.00 (see Appendix 3) hence, cutting down cost incurred in buying and maintaining drying machines/equipment. Also, the system helps maintain the quality of clothes by proving natural and efficient clothes drying technique.

7.2 Limitations

The design and prototype implementation of the automatic retractable clothes drying rack was successful. However, due to some implementation constraints, some parts of the system did not function as expected. The following are some constraint in the performance of the implemented prototype.

1. The coupler for the stepper motors and the leadscrews were 3D printed (see Figure 5.3). This can create an easy failure to the system and hence, the user must be printing couplers frequently.
2. The cover curtain rolled down and up with the same program as the clothes rack frame. The difficulty encountered in rolling up the cover curtain was due to the small velocity ratio (1:2) of the gears used. I believe the rolling up of the cover curtain was highly affected by friction, which was not factored into the designed and built system. The use of a higher velocity ratio gear or a higher torque motor might be a solution.
3. The hanging rods used for the drying rack is huge. This limits the user in using pegs when hanging the clothes instead, either hangers are used, or the clothes are hanged without pegs (seen Figure 6.1).
4. The drying rack is small. It can only accommodate a maximum of nine medium size clothes at a time.

7.3 Suggestions for Future Work

This section discusses suggestions for future work on the automatic retractable drying rack. The future work can be implemented after exploring measurements of improving the limitations of the design.

1. The system uses a DC battery which must be connected to the system when in use. Since the drying rack will be continuously exposed to the sun, it will be more cost effective to operate the system with solar as the source of power.
2. There is no user manually to educate the user on how the system functions. In the future, a user manual can be developed for user reference on the system functionality.

3. The automatic retractable clothes drying rack does not retrieve the clothes when they are dried. A timer can be incorporated into the design to automatically retrieve and shut down the system when the clothes get dried.

References

[1] L. Amekudzi *et al.*, “Variabilities in Rainfall Onset, Cessation and Length of Rainy Season for the Various Agro-Ecological Zones of Ghana,” *Climate*, vol. 3, no. 2, pp. 416–434, 2015.

[2] S. Kumar, M. Selvaganapathy, S. Siddharth, and G. Kumaresan, “Design and Experimental Study on Automatic Cloth Retrieval and Drying System,” *Int. J. Adv. Res. Ideas Innov. Technol.*, vol. 3, no. 2, pp. 49–57, 2017.

[3] X. Jia and C. Chu, “Design of Intelligent Hanger Based on Single Chip and Pro-E,” pp. 131–137, 2013.

[4] P. Bendt, “Are We Missing Energy Savings in Clothes Dryers?” pp. 42–55, 2010.

[5] “No Title.” [Online]. Available: http://nymag.com/strategist/article/best-clothes-drying-racks.html. [Accessed: 09-Feb-2019].

[6] P. Hegade, S. Nayak, P. Alagundi, and M. R. Kiran, “Automatic Protection of Clothes from Rain,” vol. 5, no. 4, pp. 363–366, 2016.

[7] L. S. Cutinha, V. Pai, and B. Sadhana, “AUTOMATIC CLOTH RETRIEVER SYSTEM,” pp. 243–246, 2016.

[8] J. Marek, “Choosing Between Electromechanical and Fluid Power Linear Actuators in Industrial Systems Design,” *Thomson Linear Motion*.

[9] T. Editor, “Engineering Refresher : The Basics and Benefits,” pp. 1–4.

[10] S. Motor and L. Actuator, “Motorised Lead Screws.”

[11] D. Montone, “Applying motors in linear motion applications.”

[12] H. O. W. T. O. Pick, “Motors for Linear Motion.”

[13] I. Circuits, “Stepper motor and driver selection,” pp. 1–12, 2000.

[14] “FAQ: What are stepper drives and how do they work?” [Online]. Available: https://www.motioncontroltips.com/faq-what-are-stepper-drives-and-how-do-they-work/. [Accessed: 15-Jan-2019].

[15] G R Sinha, “Introduction and Classification of Freight,” no. 2, pp. 2–4, 2017.

[16] D. F. Da Silva and D. Acosta-Avalos, “Light-dependent resistance as a sensor in spectroscopy setups using pulsed light and compared with electret microphones,” *Sensors*, vol. 6, no. 5, pp. 514–525, 2006.

[17] H. Farahani, R. Wagiran, and M. N. Hamidon, *Humidity Sensors Principle, Mechanism, and Fabrication Technologies: A Comprehensive Review*. 2014.

[18] C. H. Circuits, T. F. Technology, and B. Automation, “Rain Sensor.”

[19] O. U. Raymond, K. S. O, Y. A. Adekunle, and O. Awodele, “Application of Microprocessors,” vol. 3, no. 4, 2013.

[20] S. Rostam, A. K. Ali, and F. H. Abdalmuhammad, “Experimental Investigation of Mechanical Properties of PVC Polymer under Different Heating and Cooling Conditions,” vol. 2016, 2016.

[21] R. Griffin, A. Texas, and R. B. Griffin, “AC 2004-145 : USE OF CAMBRIDGE ENGINEERING SELECTOR IN A MATERIALS / MANUFACTURING COURSE Use of Cambridge Engineering Selector in a Materials / Manufacturing Course,” 2004.

[22] E. Labašová, “FACULTY OF MATERIALS SCIENCE AND TECHNOLOGY IN

TRNAVA DETERMINATION OF MODULUS OF ELASTICITY AND SHEAR MODULUS BY THE MEASUREMENT OF RELATIVE STRAINS," vol. 24, no. 39, pp. 85–92, 2016.

[23] J. K. Budyans, Richard G.; Nisbelt, "No Title," in *Shigley's Mechanical Engineering*, Tenth Edit., New York: McGraw-Hill Education, 2015, pp. 42–46.

[24] N. Publications, I. Journal, O. F. Innovations, and I. N. Engineering, "LITERATURE REVIEW ON FRACTURE TOUGHNESS AND IMPACT," vol. 2, no. 11, pp. 1–5, 2015.

[25] "Weight of materials.pdf.".

[26] T. Covered and C. Composition, "ASTM A36 Mild / Low Carbon Steel," pp. 1–3, 2012.

[27] T. Covered, C. Composition, P. Properties, and M. Properties, "AISI 1212 Carbon Steel (UNS G12120)," pp. 1–2, 2012.

[28] B. P. Samal, S. C. Panigrahi, and B. Sarangi, "Tensile Properties Analysis of Aluminium-Magnesium Alloys Produced by Modified Stir Casting Method," vol. 2, no. 12, pp. 869–871, 2014.

[29] K. Rassiah and M. M. H. M. Ahmad, "A review on mechanical properties of bamboo fiber reinforced polymer composite.," *Aust. J. Basic Appl. Sci.*, vol. 7, no. 8, pp. 247–253, 2013.

[30] T. Gutu, "A Study on the Mechanical Strength Properties of Bamboo to Enhance Its Diversification on Its Utilization," *Int. J. Innov. Technol. Explore. Eng.*, no. 2, pp.

2278–3075, 2013.

[31] D. Bhonde, P. B. Nagarnaik, D. K. Parbat, and U. P. Waghe, "Physical and Mechanical Properties of Bamboo (Dendrocalmus Strictus)," *Int. J. Sci. Eng. Res.*, vol. 5, no. 1, pp. 455–459, 2014.

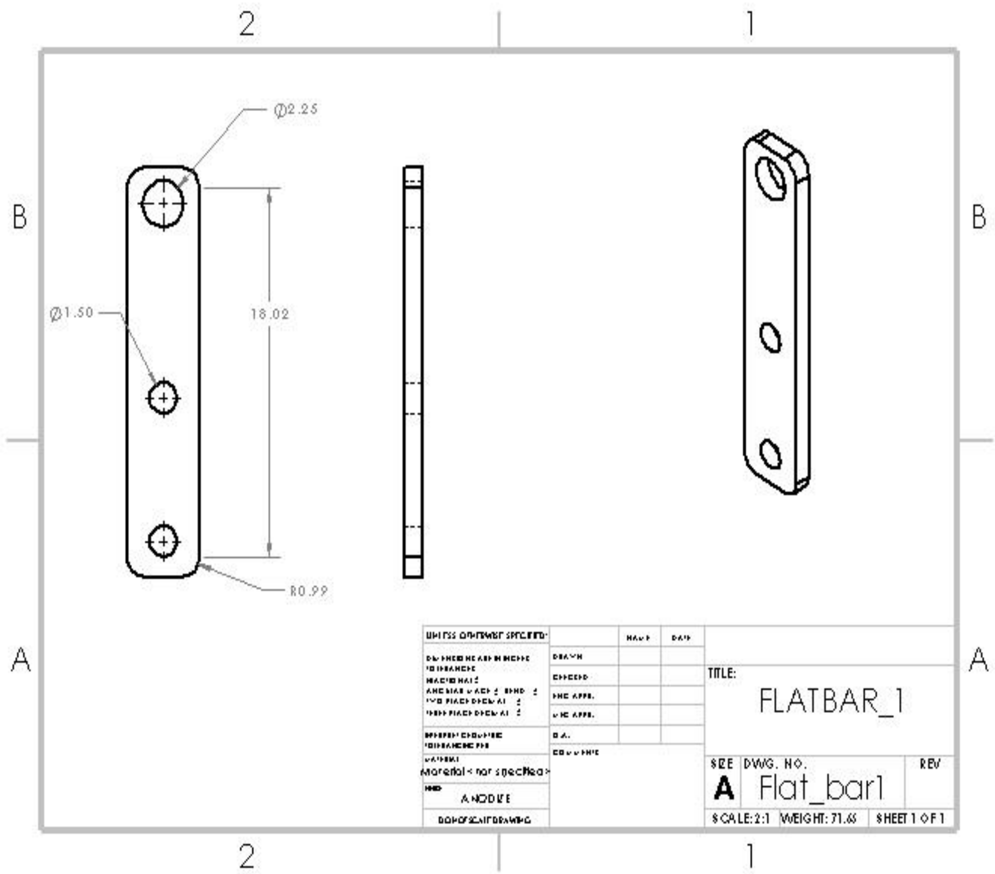
[32] J. K. Budyans, Richard G.; Nisbelt, "No Title," in *Shigley's Mechanical Engineering*, T. Edition, Ed. New York: McGraw-Hill Education, 2015, pp. 201–224.

[33] J. K. Budyans, Richard G.; Nisbelt, "No Title," in *Shigley's Mechanical Engineering*, New York: McGraw-Hill Education, 2015, pp. 666–697.

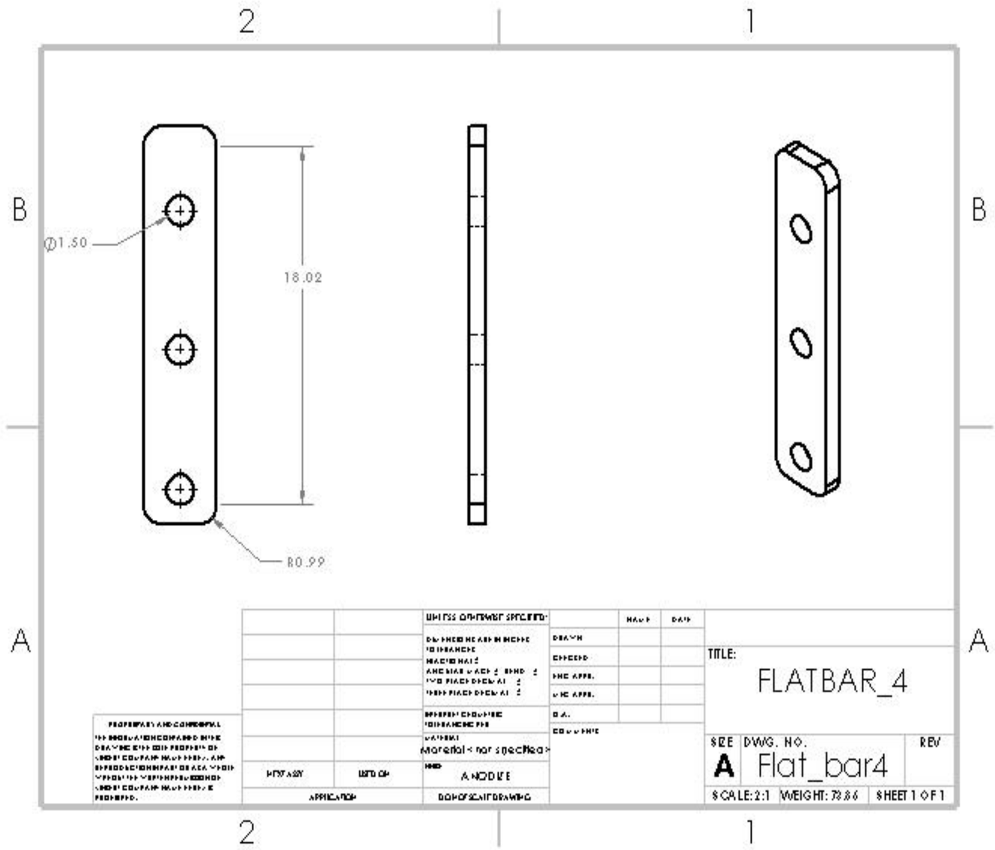
[34] S. G. Drives, "Learning Activity Collaborative," pp. 1–73.

Appendix

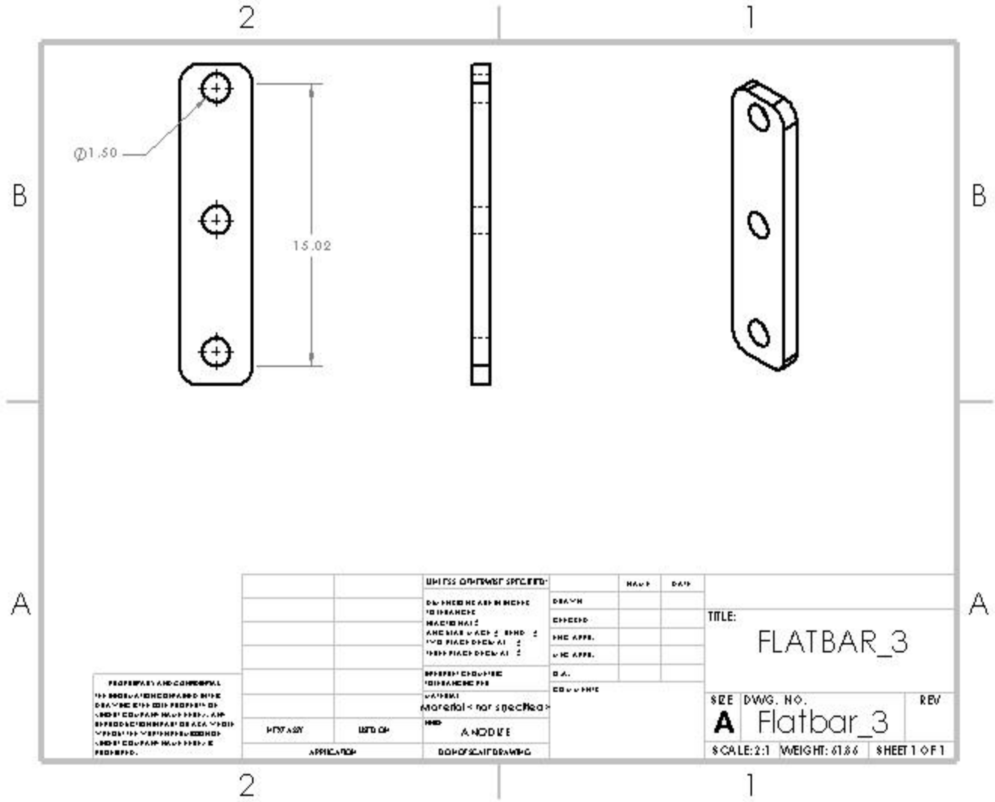
Appendix 1: Pictures of engineering drawings



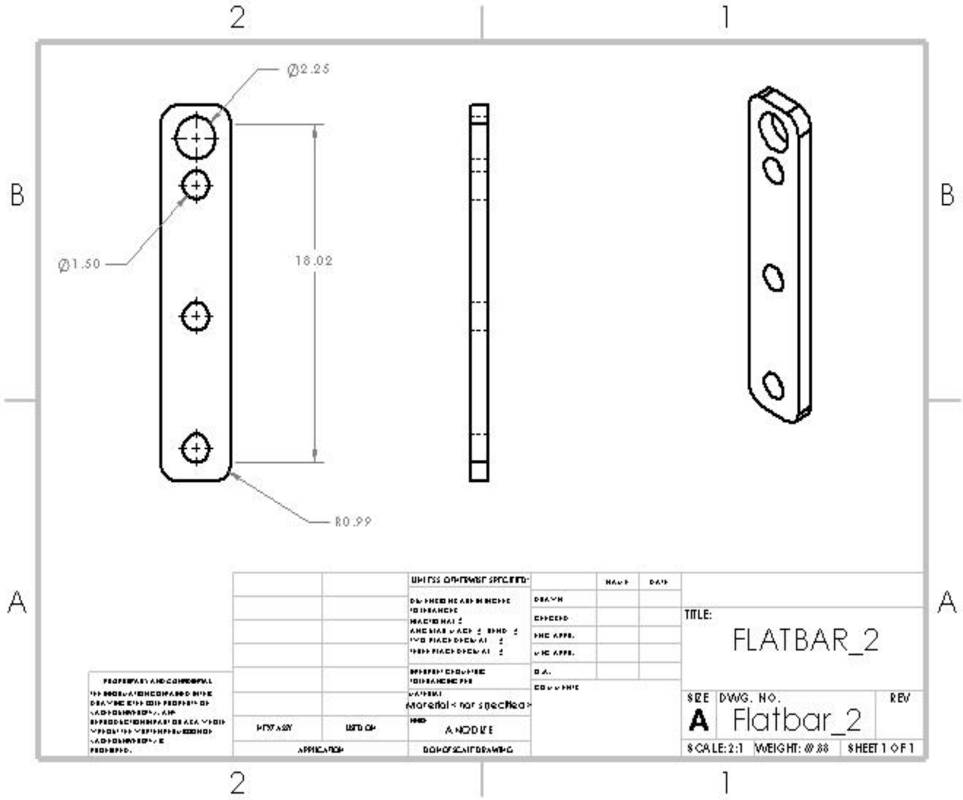
Drawing of the two front frond flat bars



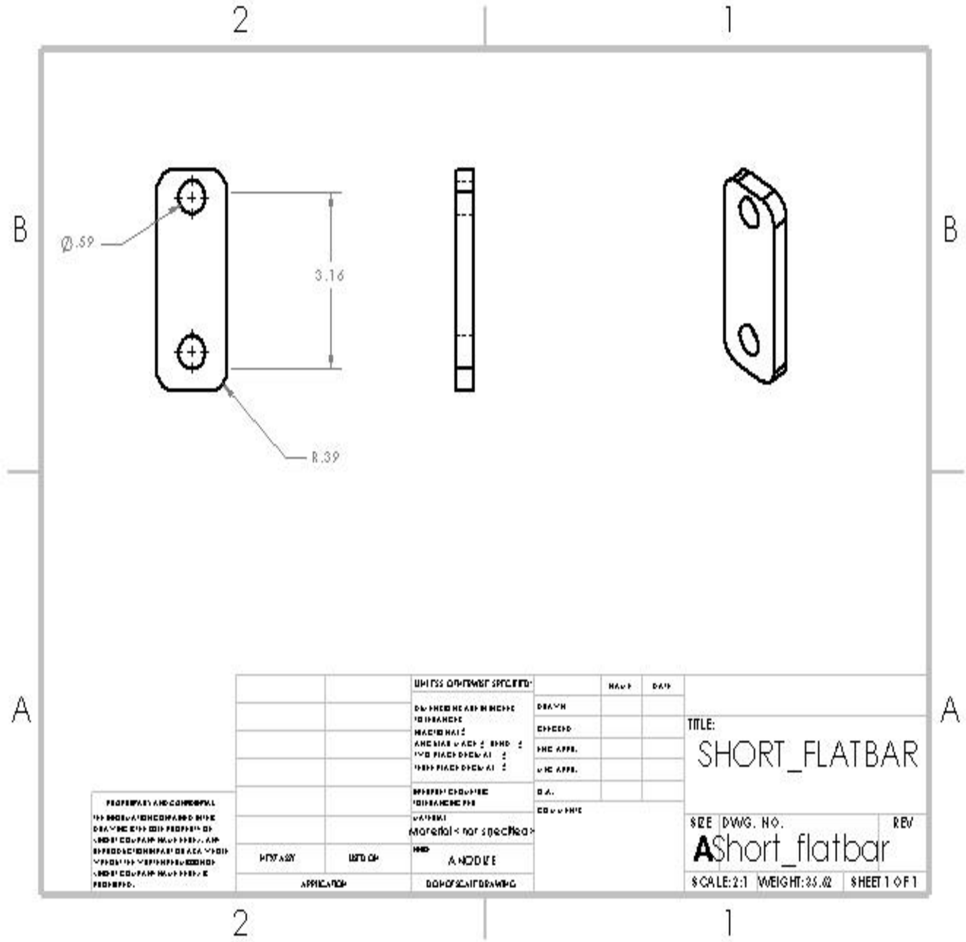
Drawing of the two back flat bars



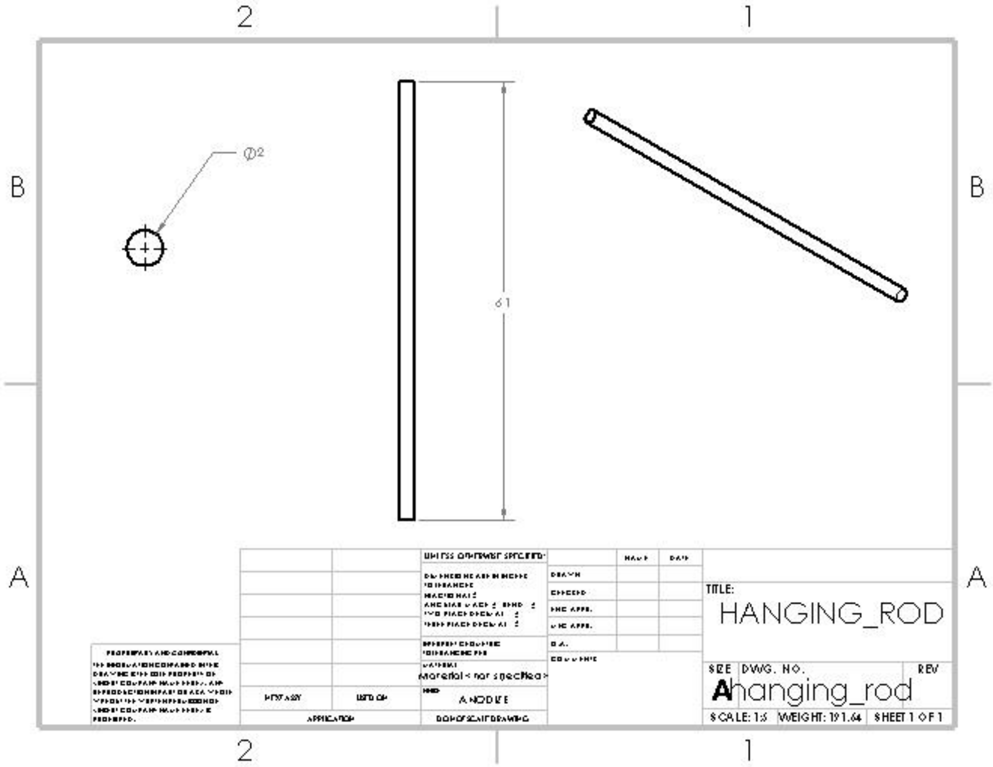
Drawing of the two medium flat bars



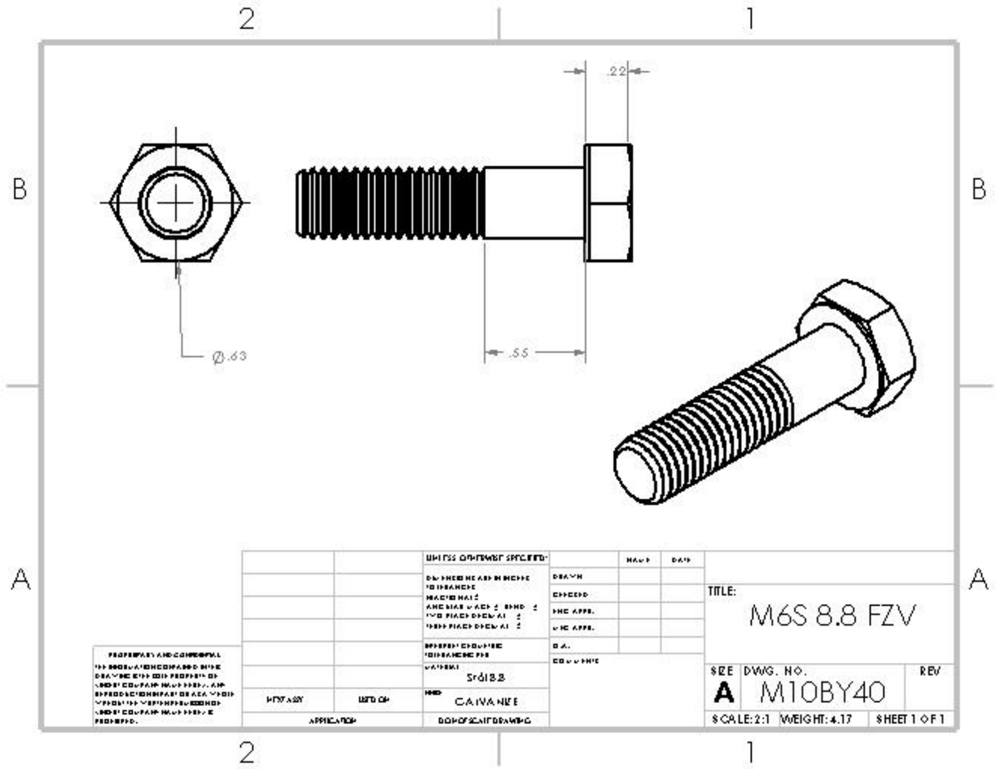
Drawing of 4 longest flat bars



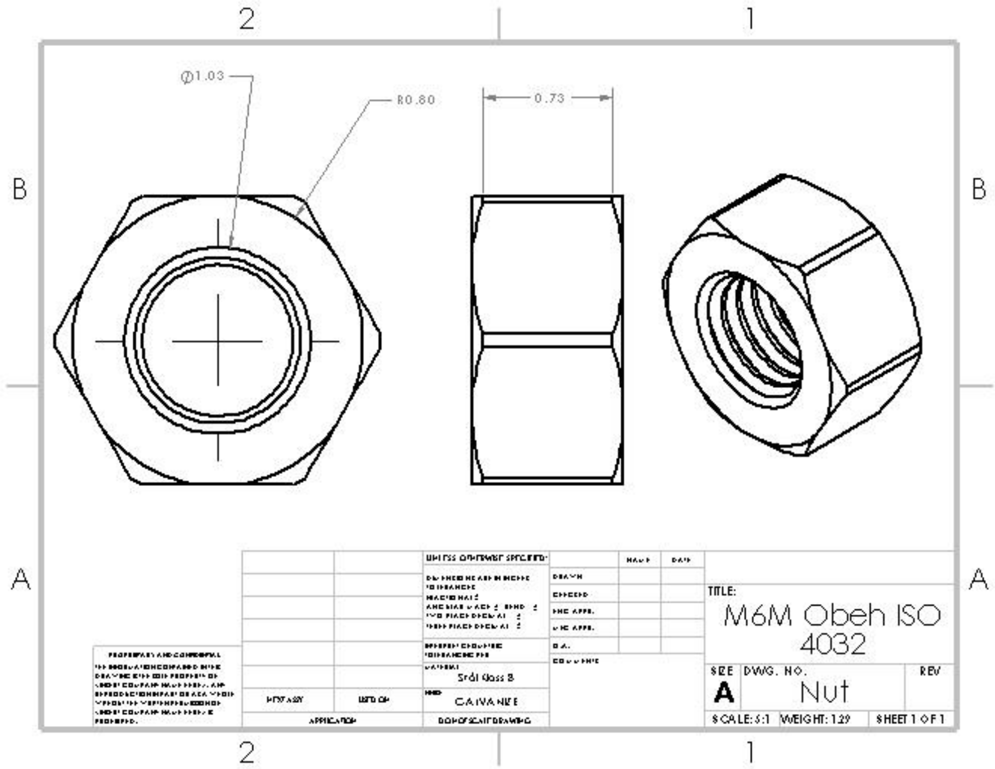
Drawing of the two shortest flat bars



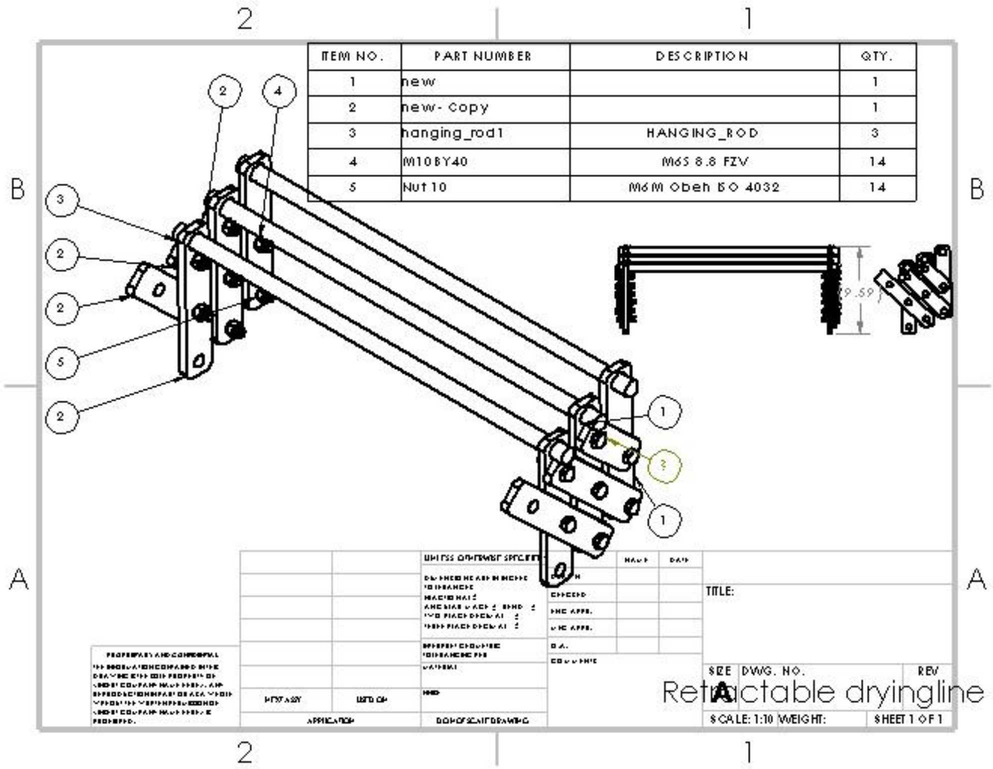
Drawing of the hanging rod



Drawing of the bolt



Drawing for the nut



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	new		1
2	new- Copy		1
3	hanging_rod1	HANGING_ROD	3
4	M10BY40	M6S 8.8 FZV	14
5	Nut 10	M6M Oben ISO 4032	14

Drawing of the drying line frame with bill of parts

***The new and new-copy on the bill of material stands for the left and right assembled frame*

Appendix 2: Arduino code

// Citing stepper motor code

// Tittle: How to Control a Stepper Motor with A4988 Driver and Arduino

// Author: Dejan

// Date: 2015

// *Availability: https://howtomechatronics.com/tutorials/arduino/how-to-control-stepper-motor-with-a4988-driver-and-arduino/*

//Main Code

```
//LCD Display
#include <LiquidCrystal_I2C.h>
#include <Wire.h>
LiquidCrystal_I2C lcd(0x3F, 20, 4);

//humidity sensor
#include <dht.h>
#include "dht.h"
#define dht_apin A2 // Analog Pin sensor is connected to
dht DHT;

//LDR
int sensorPin0 = A0; // select the input pin for LDR
int LDR = 0; // variable to store the value coming from the sensor

//water sensor
int sensorPin1 = A1;
int watersensor = 0; // Incoming analog signal read and appointed water sensor
```

```
// stepper motor
const int stepPin = 3;
const int dirPin = 4;
const int stepsPerRevolution = 100;
int en1 = 13;
int en2 = 12;
void enable() {
  digitalWrite(en1, LOW);
  digitalWrite(en2, LOW);
}
void disable()
{
  digitalWrite(en1, HIGH);
  digitalWrite(en2, HIGH);
}

void setup() {

  //LCD Display
  Serial.begin(9600);
  pinMode(en1, OUTPUT);
  pinMode(en2, OUTPUT);
  lcd.init();
  lcd.setBacklight(HIGH);

  // Sets the two pins as Outputs
  pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);

}



void loop() {
```

```
  //Reading sensor

  //Reading the humidity sensor
  DHT.read11(dht_apin);
  lcd.print("humidity = ");
  lcd.print(DHT.humidity);
  lcd.print("%  ");
  delayMicroseconds(4000);

//Reading the LDR
  LDR = analogRead(sensorPin0); // read the value from the LDR
  lcd.print("LDR = ");
  lcd.print(LDR); //prints the values coming from the LDR on the screen
  delayMicroseconds(4000);

//Reading the water sensor
  watersensor = analogRead(sensorPin1); // read the value from the LDR
  lcd.print("rainfall = ");
  lcd.print(watersensor);   //Wrote serial port of water sensor
  delayMicroseconds(4000);


  //Main code to retrieve drying line when the environment is favorable

  if (DHT.humidity < 100 && LDR < 200 && watersensor < 2 ) //low humidity and high light
intensity and no rainfall
  {
    digitalWrite(dirPin,HIGH); // Enables the motor to move in a counter clockwise direction
    for (int x = 0; x < (stepsPerRevolution * 120); x++) {
      digitalWrite(stepPin, HIGH);
      delayMicroseconds(1000);
      digitalWrite(stepPin, LOW);
      delayMicroseconds(1000);
```

```
    }
    disable();

  }



  //Main code to retract the drying line when the environment is unfavorable


  if (DHT.humidity > 100 && LDR > 200 && watersensor > 3 ) //high humidity and low light
intensity and rainfall
  {
    digitalWrite(dirPin, HIGH); // Enables the motor to move in clockwise direction
    for (int x = 0; x < (stepsPerRevolution * 120); x++) {
      digitalWrite(stepPin, HIGH);
      delayMicroseconds(1000);
      digitalWrite(stepPin, LOW);
      delayMicroseconds(1000);
    }
    disable();

  }



}
```

Appendix 3: Bill of materials with dimensions for the prototype

Parts	Num.	Cost (GHc)
Hollow aluminum bars	2 of 180cm	30.00
Lead screw	2 of 20cm	8.00
Nuts	2	6.00
Stepper motors	3 of NEMA 14	21.00
3D printed gears and couplers	2 gears and 2 couplers	-
Bearings	1 big and 2 small	20.00
Cover curtain fabric	1m	20.00
Cover curtain rod	70cm of 2cm diameter	-
Bolts and nut	14	7.00
Water sensor	2	4.00
Humidity sensor (DHT11)	2	8.00
LDR	2	2.00
LCD	1	10.00
Battery	1	32.00
Breadboard	2	6.00
Connecting wires	bung	4.00
Arduino Uno	1	20.00
Total cost		**198**

Appendix 4: List of workshop equipment and tools used

1. Shear cutter
2. Jig saw
3. Riveter
4. Welding machine
5. 3D printer
6. Pliers and screw drives
7. Electric filler
8. Hang drill and electric stand drill
9. Hammer