Automatic Rebar Bending Machine to Form Rectangular Stirrups

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Submitted to the College of Engineering in partial fulfillment of the requirements for the Bachelor degree in Mechatronics Engineering

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College of Engineering

Department of Mechanical Engineering

Hebron - Palestine

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Supervisor Signature

....

Testing Committee Signature

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Chair of the Department Signature

....

الإهداء

مع كل المحبة نهدي باقة معبقة بأريج الزهور إالى :

نهدي هذا البحث إالى سيدنا محمد صلوات الله عليه و سلم و أمته جميعاً.

إلى من لولا تضحياتهم الجسيمة لما وصلنا إلى هذه الحياة الأسرية السعيدة ... فالعلم و الإيمان بدونهم ما تجسد فينا ... إلى من علمونا التواضع و الصبر و الحياء , إلى الذين يقطر من فمهم الصدق و العفوية إلى معلمينا الأوائل ... إليكم " آبائنا الموقرين ".

إلى من تعجز أي كلمة عن شكرهن و تقديرهن لجهودهن معنا ... إلى رموز الصبر و التضحية و منابع الحنان و الإيمان ... إلى الكلمة التي تحمل معها كل معاني الحب و العطاء ...إلى من نفتخر بهن و نتمنى لهن دوام الصحة والعافية ... إلى من رضاهن أقصى أمنياتنا ... إليكم " والداتنا الغاليات ".

إلى الزهور اليافعة و الإبتسامة الرائعة ... إلى شموع الأمل و عيون المستقبل إلى من هم خير معين ... إلى سندنا ... إلى " إخوتنا الأعزاء ".

إالى الزهور في بستان القلب ... إلى شقيقات الروح ... إلى من عيونهن الحياة ... إلى من وجدنا فيهن الحب و العطاء و التواضع ... إلى " أخواتنا الغاليات ".

إلى من علمونا حرفاً في مسيرتنا التعليمية ... إلى " أساتذنا الأفاضل ".

إلى كل من مررنا بهم على درب العلم و المثابرة ... إلى " زملائنا الأعزاء "

إلى هؤلاء جميعاً

نهدي هذا البحث

شكر و تقدير

شكرنا و تقديرنا إلى دكتورنا و مشرفنا ...

د.يوسف سويطي

الذي كان بالنسبة لنا الشمعة التي أضاءت امامنا الطريق الصحيح منذ لحظة البداية فكان المرجع الذي نتعلم منه كل شيء

فشكرنا الجزيل له

Abstract (in English):

This project considers design and building an automatic rebar bending machine to form stirrups with different dimensions and sizes. The machine is proposed to be accurate and precise with fast production rate, also it must be safe and easy to program and operate.

The machine aims to form closed loop stirrups from steel rebars which used in concrete beams and columns specially for 8mm steel bars without needs human assist, this done by entering the appropriate dimensions of stirrups by the user via Human Machine Interface (HMI) then automatically the machine inserts the bar then bend it to the required stirrup dimensions based on the algorithm build in Programing Logic Controller (PLC).

Abstract (in Arabic):

إن الهدف الاساسي و المرجو من هذا المشروع هو تصميم و بناء ماكنة تقوم بثني قضبان حديد التسليح أتوماتيكاً لتشكيل الكانات بمختلف أبعادها وأحجامها ,هذه الماكنة اقترحت لكي تكون عملية الإنتاج سريعة و أكثر دقة , بالإضافة إلى ذلك أن تكون آمنة و تكون برمجتها و عملية التعامل معها سهلة.

الماكنة تقوم بثي قضبان حديد التسليح اللتي يكون قطرها 8 ملم لتشكيل كانات مستطيلة الشكل والتي تستخدم في الأعمدة والجسور الإسمنتية المسلحة دون الحاجة للقوى البشرية في عملية التشكيل.

تتم العملية من خلال عدة خطوات يتم التحكم بها عن طريق المتحكم المنطقي المبرمج المرتبط بالماكنة, حيث يقوم المستخدم للماكنة بإدخال أبعاد الكانة المراد تشكيلها عن طريق شاشة تحكم تفاعلية مرتبطة مع المتحكم ومن ثم تقوم الماكنة بإدخال القضبان و تنتهي بتشكيلها حسب الابعاد المطلوبة.

Table of Contents

List of Tables

List of Figures

1

Chapter One: Introduction to Automatic Rebar Bending Machine to Form Rectangular Stirrups

1.1 Project Overview

In the past buildings were made from mud, stone and slabs are carried by walls. These bearing walls have large dimensions and thickness which scarify most of the available space. Later when new stronger construction materials became known smaller cross section for beam and column could safely carry loads and space is more efficiently used. The most common construction materials are concrete, steel and wood. Every material has its own advantages and disadvantages. Among these three, reinforcement is more commonly used in constructing buildings, bridges, tunnels and tanks.

Reinforced concrete is achieved by successful marriage of several materials such as concrete and steel where each of them has its duties and obligations to maintain a coherent structure. Concrete has a large resistance in compression but is weak in tension and it will crack, so its needs steel to carry tension force and arrest crack so when adding steel to concrete reinforcement obtained.

According to chemical composition of steel bars which used in reinforcement cage can be categorized as carbon steel bars and ordinary low-alloy carbon steel. Generally, carbon steels with a carbon content of less than 0.25%,0.25-6%, and 0.6-1.4% are called low-carbon steel, medium-carbon steel, and high-carbon steel, respectively. Low and medium-carbon steels are mild steels, while high-carbon steel is hard steel, according to the processing method, steel bars can be categorized as hot-rolled steel bars, heat treatment steel bars and cold working steel bars.

To ensure identical distribution of tension and compression on Reinforced concrete structure, also to obtain reinforcing steel bars together so that the bar stay in position until the concrete has placed and hardened, Stirrups form which is the outer part of a rebar cage and reinforcement of the steel structure used to resist shear and diagonal tension stresses in a concrete structural member.

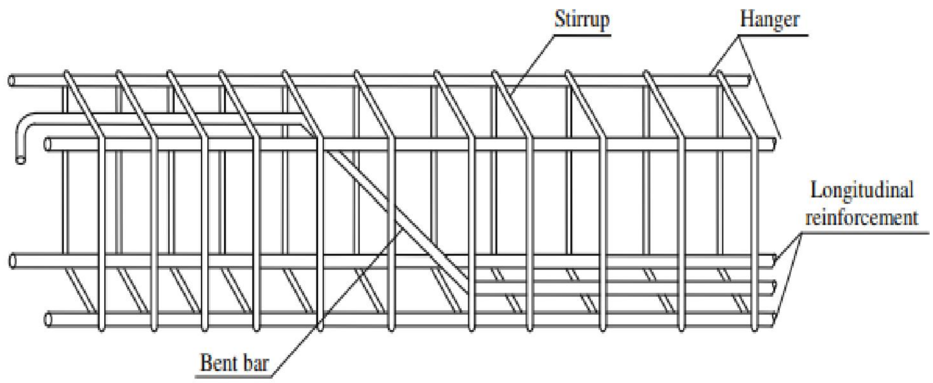


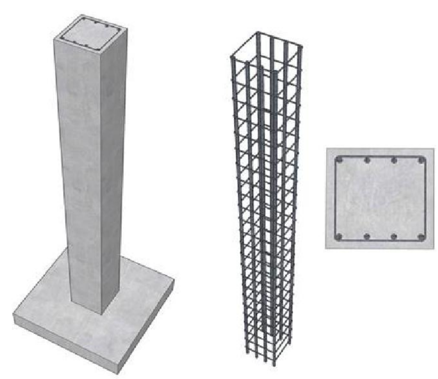
Figure 1.1:Reinforcement structure

Consequently, Stirrups have many roles which make using stirrups important in construction include with addition to the above:

1) Stirrups are provided to hold the main reinforcement Rebars together in a reinforced concrete structure.
2) In columns, stirrups are used to prevent buckling of main reinforcement.
3) In beams they prevent diagonal cracking due to shear, so they are colloquially called shear reinforcements.
4) Improve reinforced concrete ductility so, in earthquake prone zones the number of stirrups increased.

Also, stirrups have a lot of shapes according to columns and beams dimensions and stirrup application such as:

1) Closed loop stirrups:
   Closed loop stirrups are more commonly used they provide greater torsional resistance and seismic resistance they are mandated for beam with compression reinforcement.

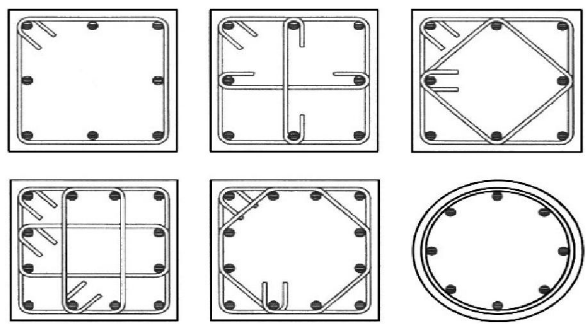


2) Open loop stirrups:
   Because of its open loop, open loop stirrup produces less reinforcement congestion all-owing easier flow of concrete during its placement.

3) Circular stirrups:
   Used in circular columns.

4) U-shape stirrups.

5) Spiral stirrups.



Due to the importance of the stirrups in reinforced construction, stirrups production should be rapid and precise production In line with the development in the field of construction and architecture, which progresses day after day, in addition to lacking of the local market for the technology in stirrups bending process, hence the idea of design and implement Automatic Rebar bending machine.

1.2 Recognition of the needs

The project idea created based on the lack of Palestinian market in the process of forming stirrups where they are formed using traditional methods, these methods are manual or half-automatic automatic which have a lot of disadvantage includes:

1) Needs operator in all process stages.
2) Wasting time (slow process).
3) Pose a risk for the operator.
4) Inaccurate process.

Achieving the optimal mechatronics design and implementation of full-automatic machine the design must meet the needs of the customer in the market of Palestine which is:

1) The machine should have user friendly interface, which is a touch screen connected with PLC, and the operator just enters the appropriate closed loop stirrups dimensions through it.
2) The process of the machine will be full automatic it doesn't need the operator in every stage of the process.
3) Improving the safety level for stirrups forming process.
4) Achieve the accuracy for stirrups dimensions.
5) The smallest size of stirrups that can be formed using this machine is 10×10 cm.

1.3 Objectives

1) Catch up with industrial development in the local market with global markets in the process of forming stirrups.

2) Save time and effort to increase the amount of production.

3) Raise the safety level for machine's operator, because he is the most important element in the production process.

1.4 Time schedule for the introduction to graduation project

Table: 1.1: Time schedule for the introduction to graduation project

No. of week / Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Identification of project idea	■	■													
Drafting a preliminary project proposal			■	■											
Introduction about project				■	■	■									
General description about project						■	■	■	■						
Mechanical design										■	■	■	■	■	■

1.5 Total cost for the project

Table: 1.2: Total cost for the project

Components	Price(NIS)
Bending Motor	1800
Feeder Motor	600
Gripper Motor	150
Plate’s Motor	250
Bending Gearbox	1200
Feeding	500
Limit switches (8)	220
PLC	1450
Encoder	600
Belt (2)	50
Bearing (18)	280
HMI	1500
Pulleys (2)	100
Switches (3)	50
Profiles	400
Sprocket (2)	80
Variable frequency drive	1400
Contactors (2)	80
Relays modules	80
Raw materials & lathing	3000
Chain	100
Covers	250
Screws, Bolts and nuts	150
Total cost	14290 NIS

2

Chapter Two: Literature Review

2.1 Introduction

This chapter concerns a review for some different principles of rebar bending machine depending on scientific papers, graduation project, in addition to the team researches in the local and global market, to get the knowledge about the technology in this field and to clarify the road map to be followed during the project implementation. Also, this reviewed includes the description of the machine that will be implemented in this project.

As mentioned above rebar bending or stirrups forming process accomplished through several methods such as, manual, half automatic and full automatic bending machines, which will describe by detailed.

2.2 Stirrups forming methods

1) Manual bending machines:

The process of stirrups forming in this machine considered as a simplest operation of bending machines where the procedure is moving the arm of bending mechanism which create appropriate bending moment about the center point of the mechanism to bend the steel bars, as shown in Fig 2.1.

But this machine has a lot of disadvantages such as, slow production process, needs a large power for bending moment, also the operator is at risk during the formation process.

2) Half automatic bending machine:

Bending process using half automatic bending machine as shown in Fig 2.2 is one of the common process of stirrups forming in the market of Palestine.

The process of stirrups forming here is almost like manual bending machine, but it is distinguished from its predecessor by fast and safe stirrups production where instead of creating the bending moment by the operator to bend rebars via mechanism arm an electric motor connecting with a gearbox perform this task after insert rebars, the motor rotates when the operator presses on momentary industrial foot pedal switch.

3) Automatic bending machine using hydraulic actuators:

In this design stirrups forming process performed by hydraulic actuators, this design was proposed by a group of students in Palestine Polytechnic Univocity (PPU) as a graduation project.

The machine working principles are; three rebars placed automatically by an external feeder then five hydraulic pistons are used for bending process where the actuators work step by step based on a programming code in Programming Logic Controller (PLC), after the stirrups forming process complete a metal piece have L shape connected with a chain gear mechanism drags the stirrups far away from the machine table.

Although, the stirrups forming process is a full automatic process but has a several drawbacks includes:

- Manual adjustment of the dimensions between the hydraulic actuators.
- Stirrups dimensions depends on the dimensions of the machine table.
- Using five actuators, leading to relatively high cost of the machine.

4) CNC rebar bending machine:

In this part of literature review CNC rebar bending process will be discussed relevant to scientific papers and researches via the Internet because this technology is not available in the market of Palestine.

Scientific papers which discussed are:

A. "DEVELOPMENT AND FIELD EXPERIMENTS WITH A FULLY AUTOMATED REBAR CAD/CAM SYSTEM [3]"

The paper describes the development of a fully automated rebar manufacturing machine, using current technology of computerized numerically controlled machines. The development involved a graphic simulation system. The resulting machine receives the raw material in a discrete form and finite lengths. The raw material is fed to the machine, bent, cut to size and collected - all done automatically. The paper also describes an actual field experimentation with the fully automated CAD/CAM system in a large rebar manufacturing plant. The experimentation was based on the integration of the CAD/CAM system with the existing setup of the plant. A communication link was developed to enable the data to be transferred after being extracted and processed by the CAD/CAM system.

The author explains in this paper the Fully Automated REBAR Manufacturing Plant:

- Raw material feeding system; the raw material feeding system was designed for the continuous flow of raw material into the machine, in spite of it being supplied to the plant as discrete bars of a finite length. The containers are tilted (about 20^{o}) to assist the bars in their slide towards the exit.

- Cutting and bending system; The machine has two bending heads, which comprise means for longitudinal motion, a table, a pulling system, and a cutting head. The actual bending operation is done with the bending heads. The bar enters the bending head, a stator grips it and a rotor starts rotating - the direction and rotation angle being determined by the desired bar shape. The bending operation is inaccurate because of the "spring-back" effect, which is the major obstacle to the accurate bending of a rebar. The spring-back problem can be solved with an intelligent control system, such as the one being developed in North Carolina State University.

- Excess bar handler; bar. In most cases, after cutting all the rebars from a raw-material-bar there is an excess bar remaining, which is shorter than the desired length for the next rebar.

- Temporary storage of finished products; The FPTS is mounted on tracks, which enables it to move from the empty trolley stack, to its location underneath the cutting and bending machine. When a rebar is finished it slides down onto the FPTS. The machine controller determines the location of the rebars fall. When a trolley is full, it is automatically moved to the stack of loaded trolleys and is replaced by an empty trolley from the empty-trolley stack.

B. “PROCESS DRIVEN AUTOMATED REBAR BENDING [4]”

This paper presents a new concept for rebar bending, which is based on merging the advantages provided by integrating electronic sensors, computer-controlled motors, and data communication with a personal computer. The complexity of predicting the spring back of rebar through pattern recognition and impedance control are also being discussed. It is shown how such a system could reduce costs associated with trucking, handling, site storage, and wasted time due to short shipments, late deliveries, change orders, and inappropriate batching of the reinforcement bars.

C. “INTELLIGENT CONTROL FOR ROBOTIC REBAR BENDING [5]”

The robotic bending of straight rebar has the potential to dramatically impact the production and placement of steel reinforcing bars through accurate, just-in –time fabrication. Real time adaptive control for rebar bending relies upon the establishment of control laws based upon models that accurately describe the rebar bender and the rebar. This paper has presented the type of data used for the development of a model for the rebar and has described the prototype automated rebar bender that is being used to obtain this data and to conduct experiments to test control laws developed from this data. Initial analysis of pattern information reveals a strong potential for establishing the control laws needed to have intelligent control for accurate bending through spring back compensation.

5) Automatic Rebar bending machine:

Automatic bending machine is the machine which will be designed and implement in this project where the machine construction will be same as the half automatic bending machine in bending process but in this machine the process will be different in insert the rebar into the machine, this machine will have a feeder clamped the rebars until reach the appropriate dimensions.

3

Chapter Three: Project Methodology

Project Methodology

After discussing the problem, the suggested solution for this problem is to design a full automatic REPAR bending machine, to get this solution mechatronics design must Intervenes. To achieve best mechatronics design, the design of this machine passes through several steps includes:

1) Conceptual design.
2) Describe the mechanical design using Solidworks software.
3) Select required components according to machine design such as mechanical, electrical, hydraulic and measurement parts.
4) Chose appropriate material and dimension for machine design.
5) Set the working principle of the machine.
6) Machine assembly.
7) Testing.

- **Conceptual design:**

The conceptual design of this project goes through several stages to meet the best design of automatic rebar bending machine.

- First Stage includes:

Design the bending machine mechanism which consists several parts Figure3.1:

1- Fixed pin.
2- Rotating pin.

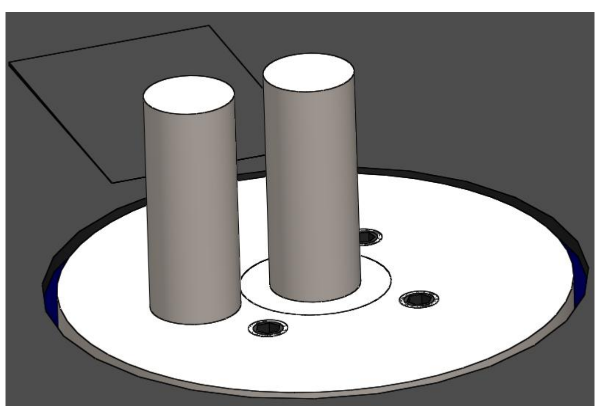


Figure 3.1: Bending part

- Second Stage:

  After study of a set of feeder's design alternatives the gear with chain is best design because it is faster than other designs, more accurate and easy control.

  The following figure shows the feeder mechanism:

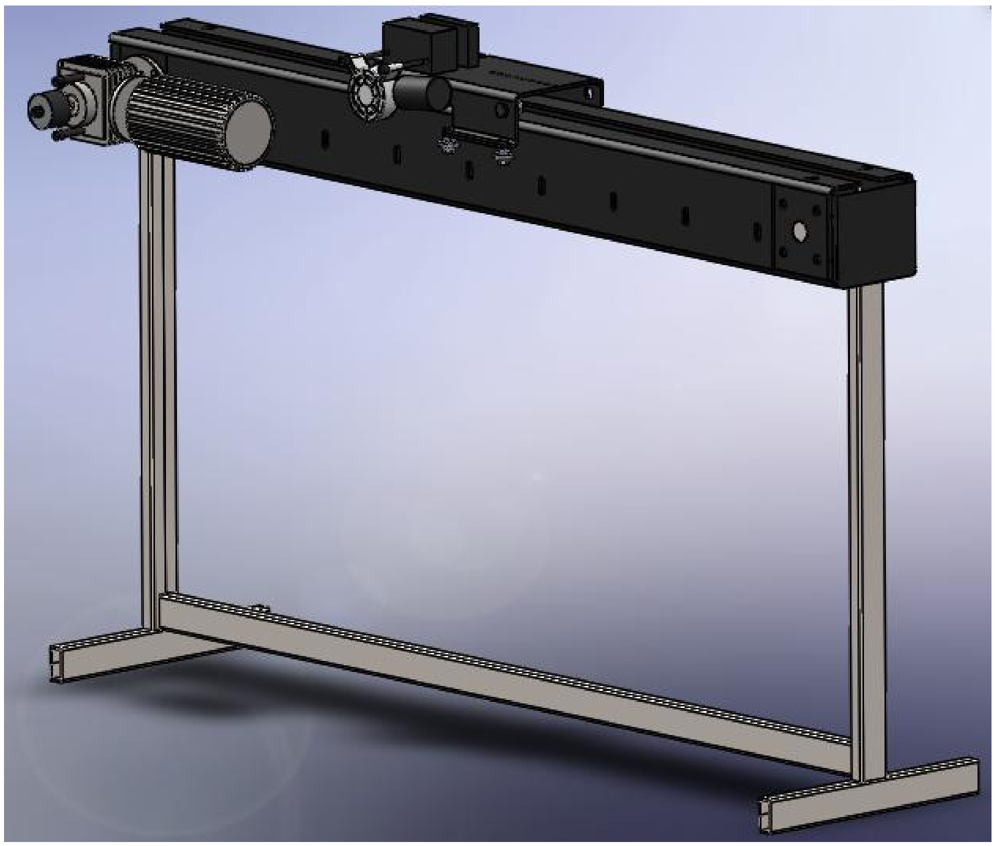


Figure 3.2: Feeder mechanism

- **Mechanical design using Solidworks**

  There a lot of software used for three-dimensional design, in this project Solidworks is adopted software which has many of features, through Solidworks the motions, mechanisms and mechanical structure will be described clearly.

- **Select required components according to machine design such as mechanical, electrical, hydraulic and measurement parts**

1. Mechanical components which include:

   Feeder table, gear with chain, clamping unit, bending table, bender mechanism which connect directly with the gear, gearbox the coupling between motor and bender mechanism.

2. Electrical components:

   Induction motor with break connect with bender mechanism.

   Feeder motor which connect with the feeder gear.

   Programmable Logic Controller (PLC).

   Human machine interface (Touch screen).

3. Measurements components “Sensors”

   Rotary Encoder.

   Limit switches.

- **Design appropriate material and dimension of mechanical design**

material and dimensions will be selected based on the analysis of the load and force based on the available material and part dimension in local market.

- **Describe the principle working of the machine**

On this stage the machine working principles must be clarify after choosing the mechanical and electrical parts, sensors.

Then describe the steps of working which the machine does, and working algorithm will represented by ladder logic, this logic is programming language for the PLC.

- **Assembling stage**

After the design of all parts, assembly stage will have done step by step for each part:

1. assembling Bender table:

the bender table contains bender mechanism, electrical motor, gearbox to couple between the mechanism and motor.

2. assembling feeder system:

the feeder system includes two gears, chain, grip unit, electrical motor, rotary encoder and proximity sensor.

3. After the assembly of all parts PLC will connecting with the system.

- **Testing**

After assembling stage done completely. Firstly, test the feeder system, if the system run correctly then test the bender mechanism if the mechanism run successfully connect all the parts together.

4

Chapter Four: Conceptual design

4.1 Introduction to Conceptual design

Conceptual design is an early phase of the design process, in which the board outlines of function and form of the machine and its process is articulated.

Conceptual design of this project contains the design of the machine and the process of the machine.

4.2 Machine parts

The main parts of Automatic rebar bending machine:

- Bending part.
- Feeding part.

4.2.1 Bending part which includes:

1. Machine frame: is the frame which carries bending part like induction motor, gearbox and others.

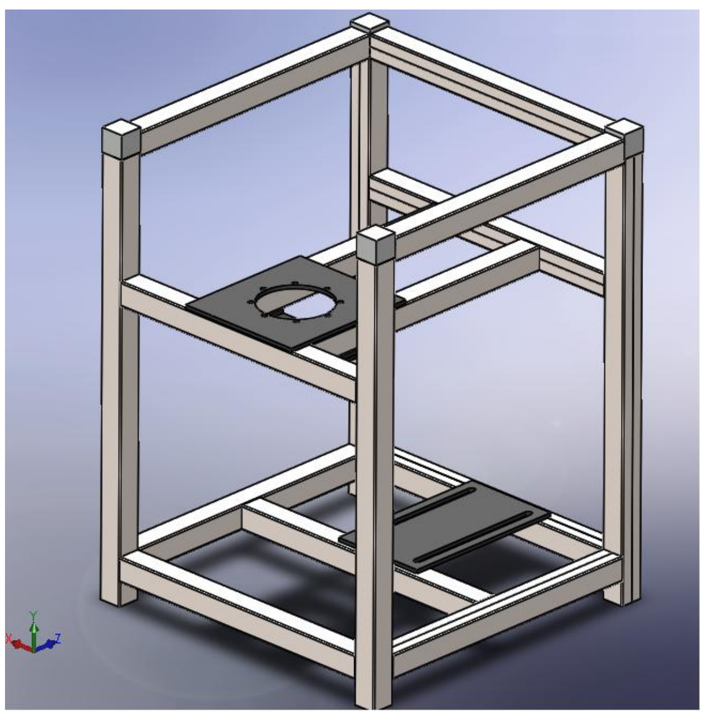


Figure 4.1: Machine frame

2. Center pin and rotating pin:

   The pins used in bending stage the first one is fixed and the bending former pin rotate 90deg about fixed pin
   Choosing of pins dimensions and material is detailed in mechanical design chapter.

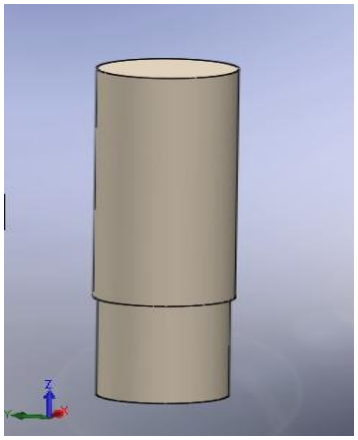


Figure 4.2: Center pin

3. Bending disc:

   The disc where the bending pins and gear box shaft in addition to cam limit switch are installed to it.

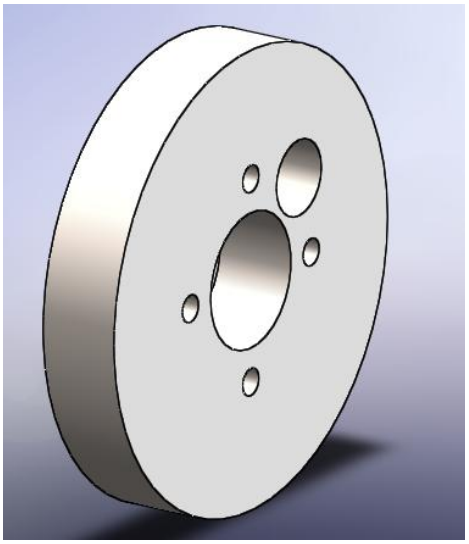


Figure 4.3: Bending Disc

4. Plate’s mechanism:

   This part of machine designed to obtain all of rebar’s at the same level when the operator put them on the machine.

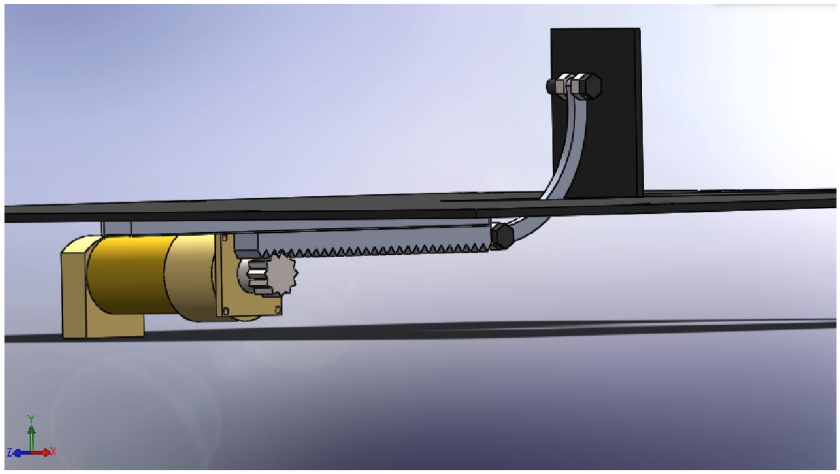


Figure 4.4: Plate's mechanism

5. Worm gearbox:

   Worm gear box which assembled between the induction motor and bending disk used for reduce the bending speed and increasing the bending moment where the required gear ratio is calculated at mechanical design chapter.

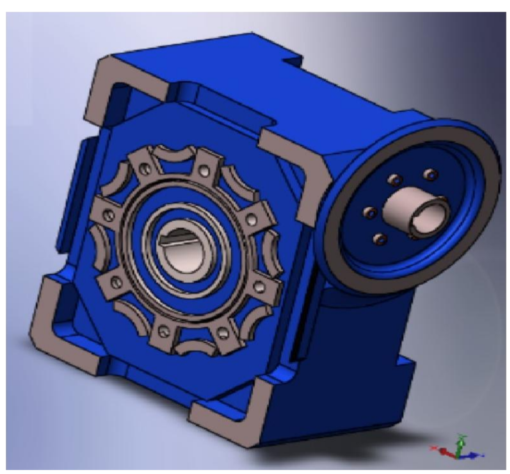


Figure 4.5: Warm gearbox

6. Three phase induction motor:

   Is the motor which driving bending process.

Figure 4.6: Three phase induction motor

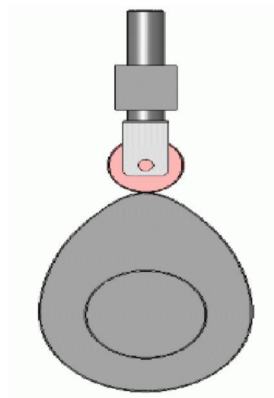
7. Limit switches:

   There are two limit switches for zero position and 90deg position, Fig 4.7.

Figure 4.7: Limit switch

8. Cam limit switch:

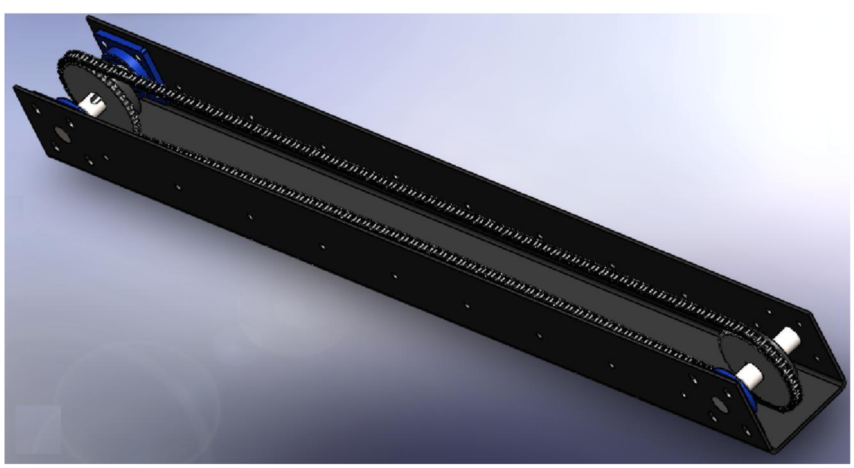
   A small piece of metal installed at bending disc, when this cam touch one of limit switches give a signal to detect the position of rotating pin at zero or at 90deg position.



4.2.2 Feeding part which contains:

1. Chain and sprocket mechanism:

   The mechanism which moves rebar onto feeding system, Fig 4.9.



Choosing of this mechanism is the best compared with other alternatives such as:

a. Two pulleys with encoder design:

Using two pulleys in this design as in Fig (4.10) to feed steel bars in the bending machine and using encoder which connect with the pulley to determine stirrups dimension, but this design has a problem; the slip of the bar when pass through pulleys that leads to get wrong in stirrups dimensions.

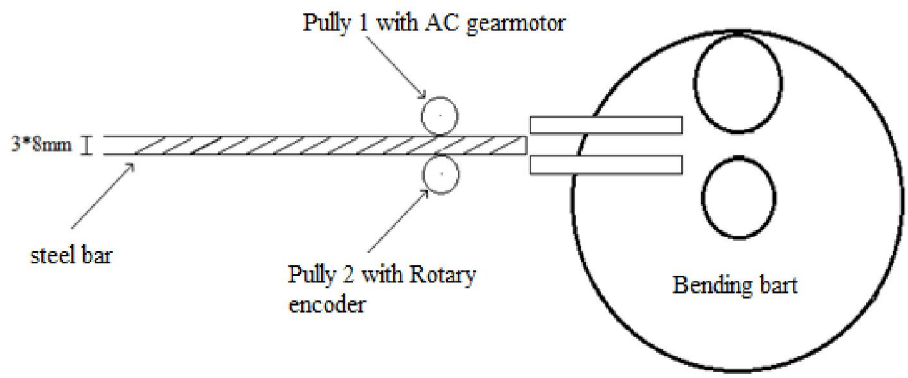


Figure 4.10: Two pulleys with encoder design

b. Pulley with power screw feedback design:

In this design the pulley used as the first design but the measurement system here is different by power screw with stop plant where, the screw moves to the desired length and when the bar touch this plate electric signal generate to stop pulley which feeds the bar.
The advantage of this design is give accurate dimension where the slip problem is solved, but the length of the stirrups will be limit by the screw length.

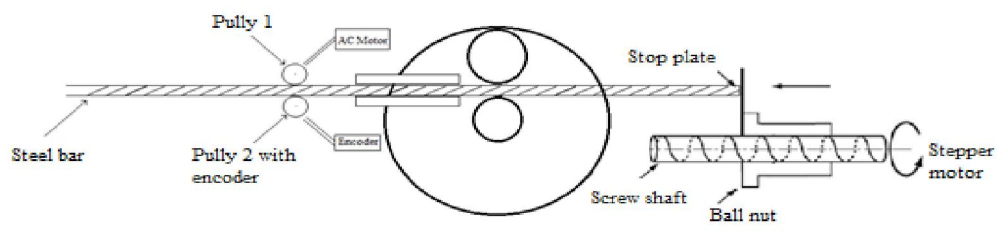


Figure 4.11: pulley with power screw feedback design

c. Feeding by power screw with stepper motor design:

In this design, the bar will feed by grip the bar on the power screw table, also the control using stepper motor is open loop control that means reduce the components compared with previous design.
Therefore, this design provides long stirrups length but the power screw is slow.

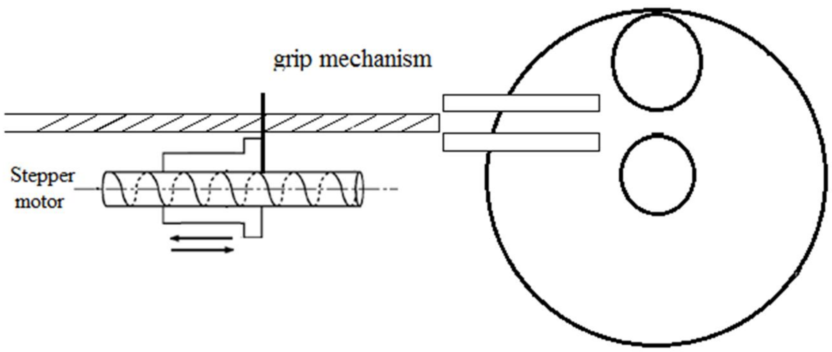


Figure 4.12: power screw with stepper motor design

2. Gripping unit:

Gripping unit hold rebar through entering process of feeder.
This unit clamps and unclamps via DC motor which connected with gripping screw.

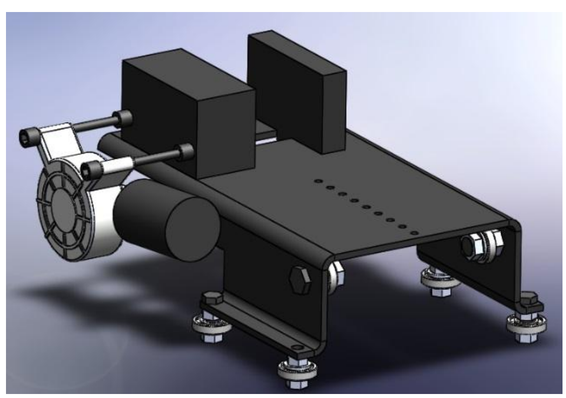


Figure 4.13: Gripping unit

3. Three phase induction motor:

   The motor which driving feeding part, Fig 4.14.

Figure 4.14: Three phase induction motor with flange

4. Worm gearbox:

   Worm gear box which will connected between the induction motor and sprocket Fig 4.15, used to reduce the motor speed where the required gear ratio is calculated at mechanical design chapter.

Figure 4.15 : Warm gearbox

5. Rotary encoder:

   Is an electro-mechanical device that converges the angular position of a worm gear output shaft to a digital signal used in PLC program to determine the stirrup dimensions. Fig 4.16 shows rotary sensor.

4.3 Working principle of the machine:

This section describes the working process of rebar bending machine

1) The operator inters the required dimensions of closed loop stirrups via touch screen as shown in Fig 4.17, then click on start.

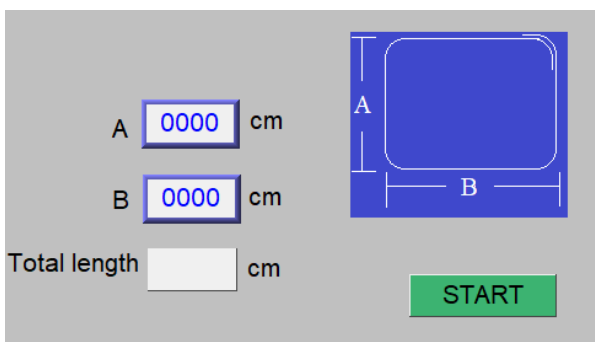


Figure 4.15: The operator inserts the appropriate dimensions

2) After the operater enters the start button another screen apperes Fig 4.18 ,when he put rebars on its place while plate up Fig 4.19 click on start cycle then machine starting the process

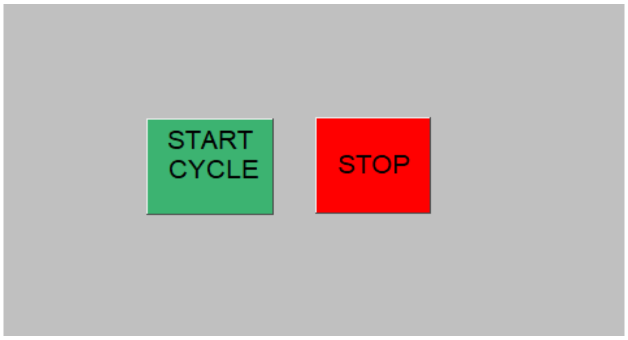


Figure 4.16: Operator select start cycle

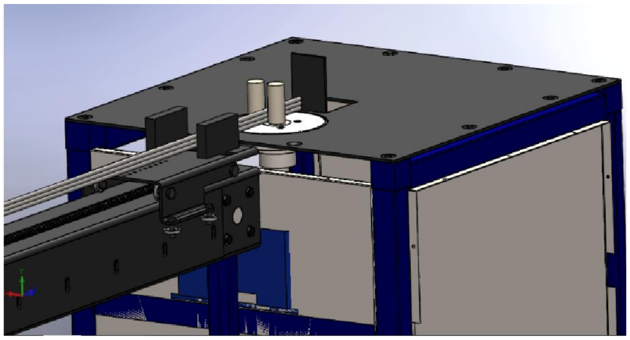


Figure 4.07: First place of rebars

3) Griping unit which is on the feeder chain clamps rebar as shown in Fig 4.20, then plate down

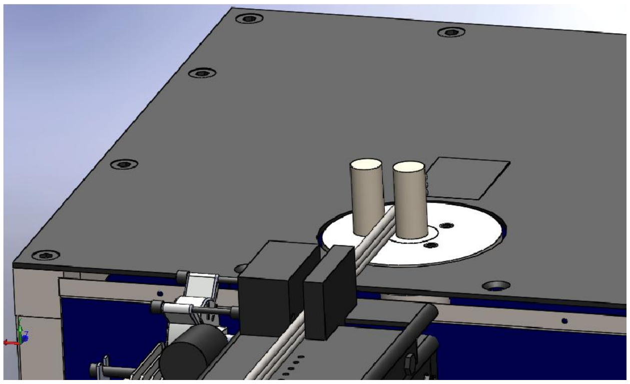


Figure 4.20: Clamp rebars

4) Bending mechanism bend the first corner from zero position to 90deg then go back as shown in Fig 4.21 and Fig 4.22.

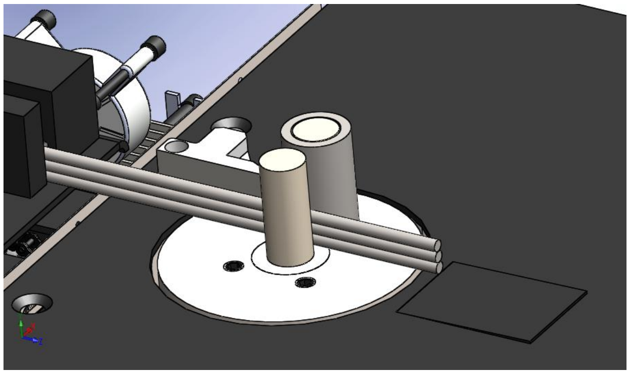


Figure 4.21 Before bending corner

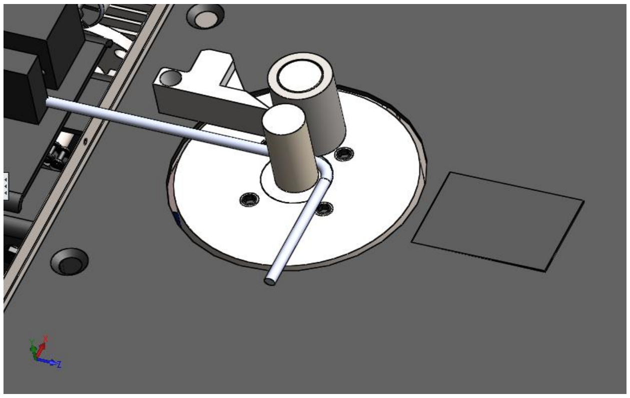


Figure 4.22: After bending corner

5) Feeder's motor run in reverse direction Fig 4.23

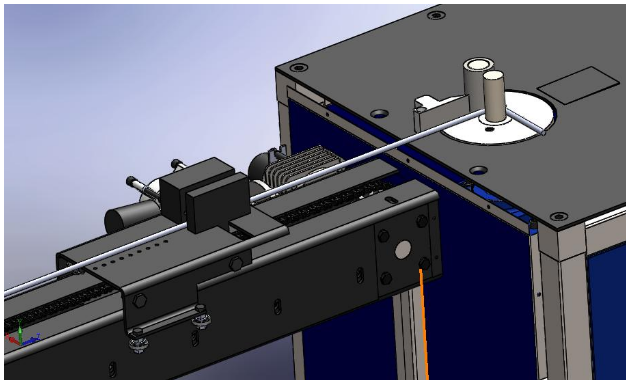


Figure 4.23: Feeding motor run in reverse direction

6) Rotary encoder sensor shown in Fig 4.24 connected with feeder's gearbox measured the dimension of the corners when the motor run in reverse direction.

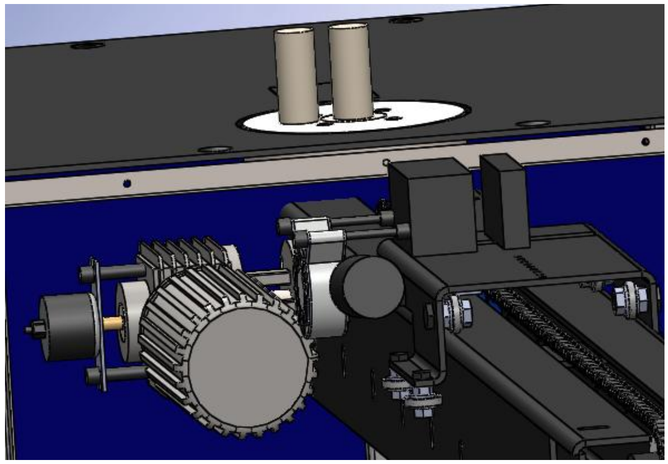


Figure 4.24: Rotary encoder assembled with gearbox

7) Then feeding motor runs in forward direction until it reaches the limit switch which locates at the beginning of the feeder.

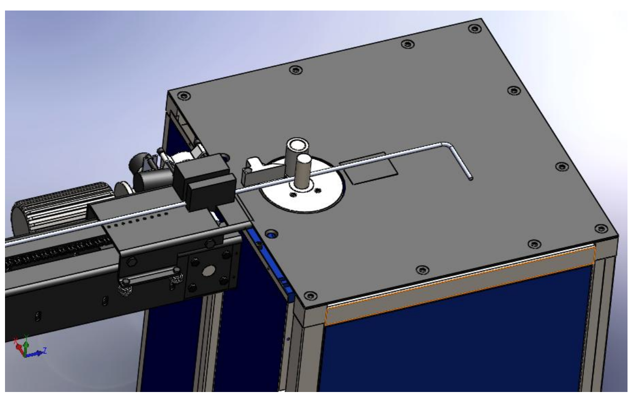


Figure 4.25: feeding motor run in forward direction

8) Bending mechanism rotates 90° CW from zero position to 90° position detected by limit switch 1 and limit switch 2 respectively, then rotates 90° CCW and returns to zero position. Fig 4.26 show this process.

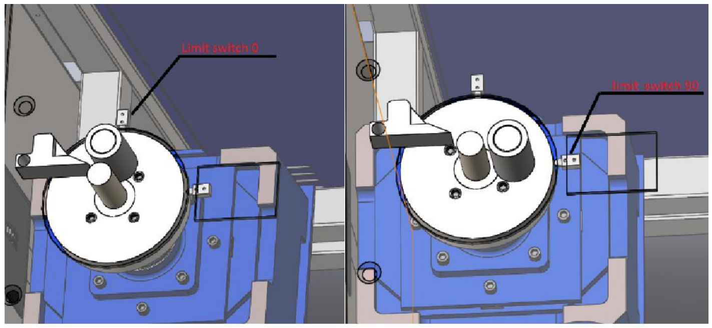


Figure 4.26: Bending mechanism at 0 and 90 deg position

9) The same process as in steps 6,7and 8 repeated for all stirrup corners from the first corner until fourth one, shown in following figures:

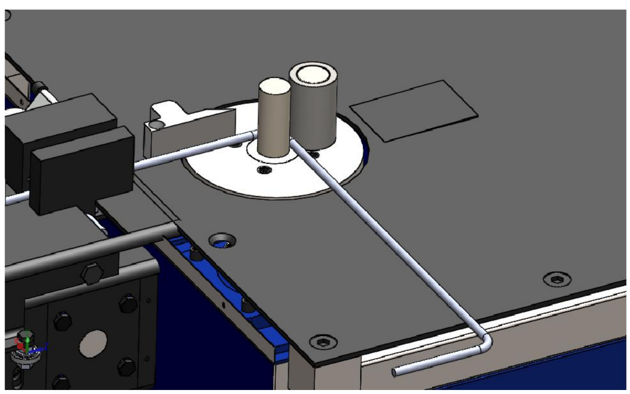
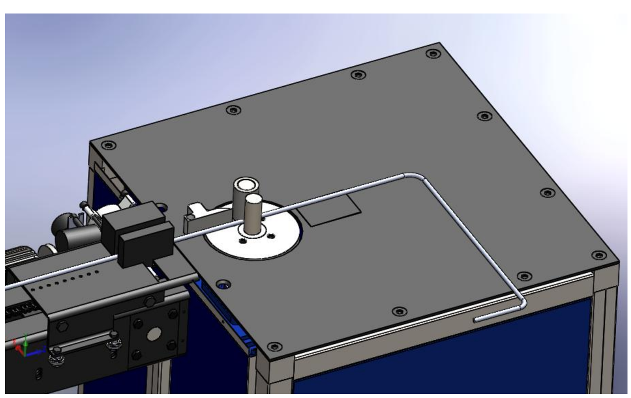


Figure 4.27: second corner



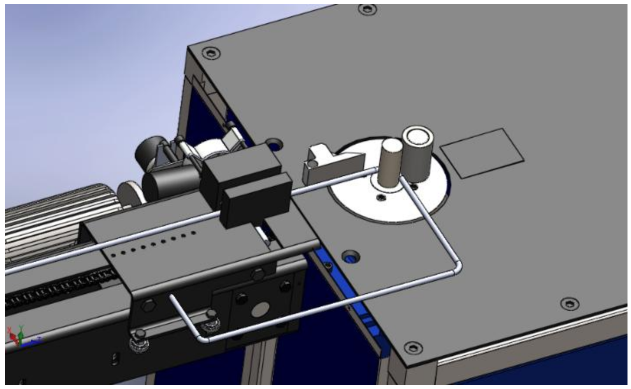


Figure 4.29: Third stirrups corner

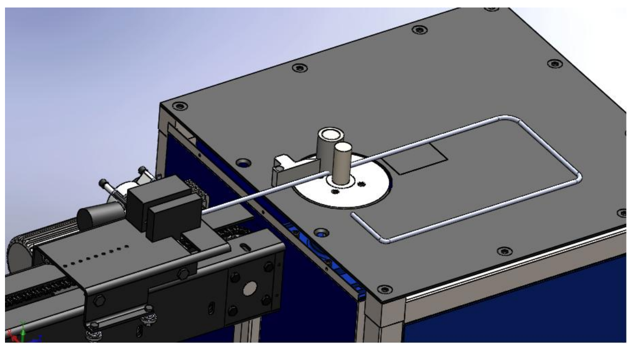


Figure 4.30: Feeding third dimension

10) For final corner, gripping unit unclamped steel bars then bending mechanism act as in step 8.

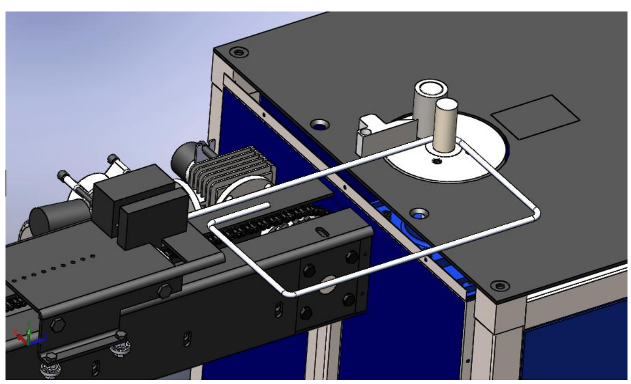


Figure 4.31: Forth corner and Gripping unit unclamped

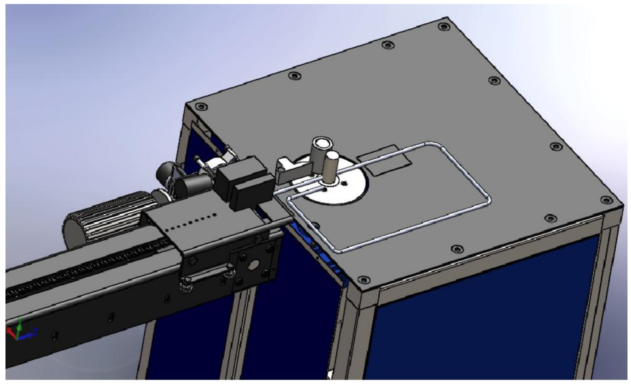


Figure 4.32: feeding last dimension

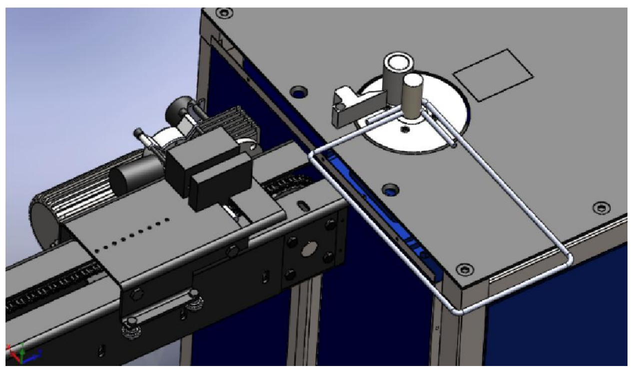


Figure 4.33: Last corner and gripping unit go back

11) The operator removes stirrups from the table of the machine.

12) Machine waits operator to insert new group of rebars then click on START CYCLE on touch screen.

The final product shown in the following figure:

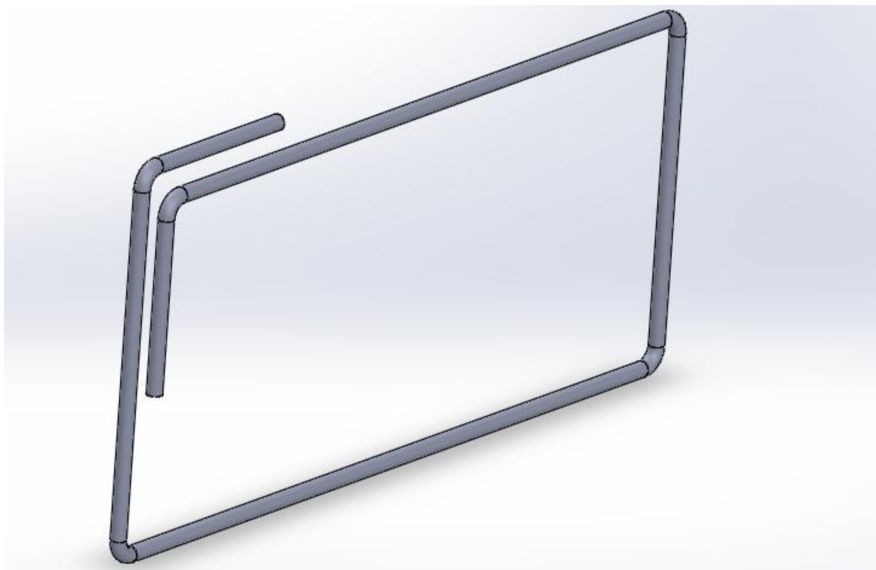


Figure 4.35 : Final product

5

Chapter Five: Mechanical design

5.1 Introduction

Mechanical design is the most important part for any machine, so in this chapter the mechanical design for every part in the machine are detailed.

Before starting in mechanical design, the material and dimensions of the mechanical part which will be designed must be known in addition to type of load and its material properties to be on safe side.

For Automatic rebar bending machine the material which will formed has the following specifications:

- ASTM, Grade 420(60), reinforcing steel which used in Palestine.
- Diameter 8 mm.
- Yield strength 420 MPa.

Also, the shape of the closed loop stirrups which the machine will form is quadrilateral and has six sides, as shown in the following figure, and has a code 51 in Britch standard.

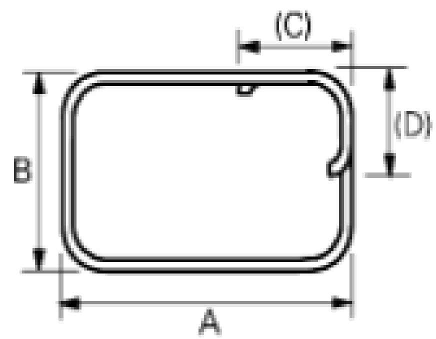


Figure 5.1: Closed loop stirrups

Closed loop stirrup contains five corners; each corner has a radius of 16mm, that means the stirrup forming process by bending machine bend the bar five times to get the final stirrup shape.

After the knowing the type of material and dimensions of stirrups an important issue should be recognize which is the stirrups forming process is a change in the shape of the metal (REBAR) under the influence of sufficient force, so the metal turns from elastic range to plastic range to obtain the stirrup corners.

5.2 Stirrups length calculations

Under British standard for code 51 **[2]**:

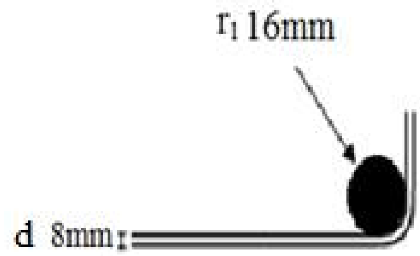
$$\text{length} = 2\,(A + B + (C)) - 2.5r_1 - 5d \quad (1)$$

C and D shall be equal and smaller than A or B.

r_1: Radius of center pin = 16mm.

d: Diameter of rebar = 8mm.

.



5.3 Calculate bending force

Normal Stresses for Beams in Bending:

The equations for the normal bending stresses in straight beams based on the following assumptions:

- The material is isotropic and homogeneous.
- The material obeys Hooke's law.
- The beam is initially straight with a cross section that is constant throughout the beam length.
- The beam has an axis of symmetry in the plane of bending.
- The proportions of the beam are such that it would fail by bending rather than by crushing, wrinkling, or sidewise buckling.
- Plane cross sections of the beam remain plane during bending.

The bending stress varies linearly with the distance from the neutral axis, y, and is given by:

$$\sigma = \frac{M\,y}{I}. \quad (2)$$

y= distance from the neutral axis.
I= Second moment of area.

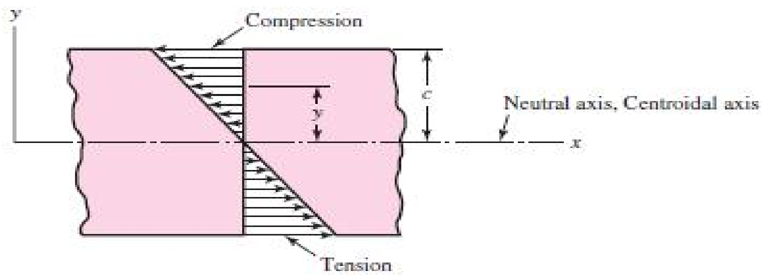


Figure 5.3: Bending stresses according to Eq (2)

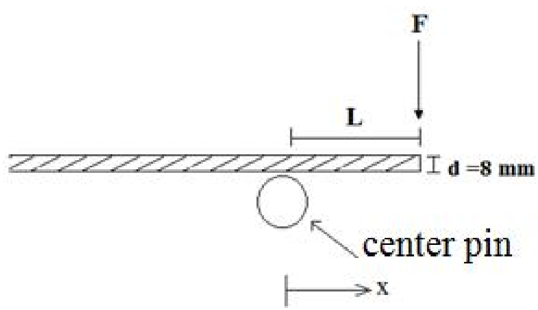
Designating σ max as the maximum magnitude of the bending stress and c as the maximum magnitude of y.

$$\sigma \ \max = \frac{M\,C}{I} \ = \frac{32\,M}{\pi\,d^3} = s_y \tag{3}$$

$$s_y = 420 \text{ Mpa} \tag{4}$$

`

At the beginning of the bending process for single rebar the required bending moment is calculated by the required bending moment is calculated by:



$$M = \frac{\sigma \max \pi\, d^3}{32} = \tag{5}$$

$$M = \frac{420 * 10^6 * 3.14 * (8 * 10^{-3})^3}{32} = \tag{6}$$

$$M = 21.1008 \text{ N.m} \tag{7}$$

The required force is calculated by

$$F = \frac{M}{L} \tag{8}$$

$F = \text{bending force.}$

$L = \text{bending arm.}$

$$L = \frac{2\pi\ r}{4} = 25.12\ mm \tag{9}$$

The bending arm is arc has a 16-mm radius and 90^o arc angle, that means

$$F = \frac{M}{L} = \frac{21.1008}{0.02512} = 840\ N \tag{10}$$

For three rebars:

The required bending moment M

$$M = 3 * 21.1008 = 63.3024\ N.m \tag{11}$$

The required force

$$F = 3 * 840 = 2520\ N \tag{12}$$

- This is the main force requried to start bending process

5.4 Bending mechanism design:

The bender mechanism is the mechanism that bend rebars and shown in the following Fig(5.4), the mechanism is made form 4340 steel and has the following spcifications:

Tensile strength $s_{ut} = 745\text{MPa}$.

Yield strength $s_y = 470$ MPa.

Hardness Brinell =217.

Modules of Rigidity $G = 79.3\text{MPa}$.

Density = $7.85 \, ^{g}/_{\text{cm}^3}$.

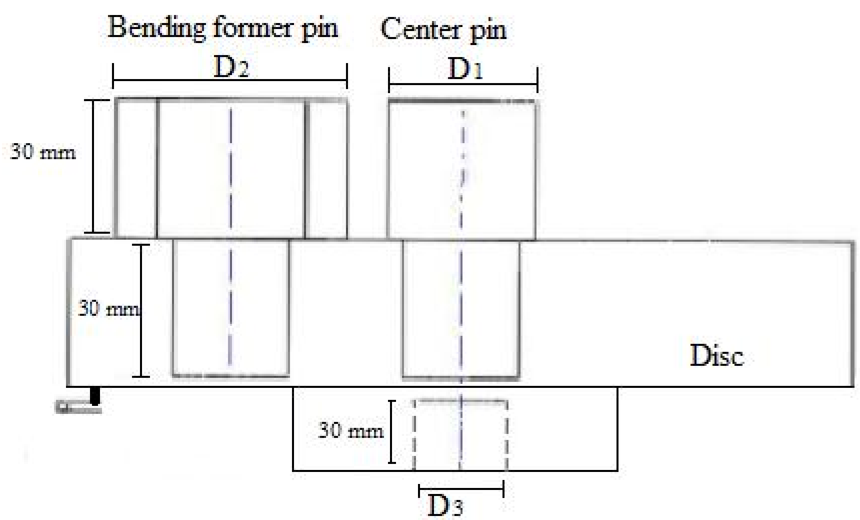


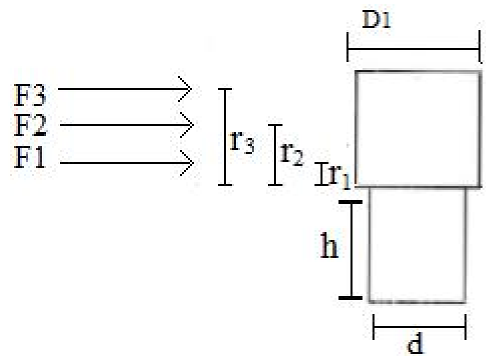
Figure 5.5: Bending mechanism

The bending mechanism contains the following mechanichal parts :

1. center pin:

According to Newton's Third Law:
when one body exerts a force on a second body, the second body simultaneously exerts a force equal in magnitude and opposite in direction on the first body. In this case the first body is bending former pin and the second body are three rebars.
that's mean: $F1 = F2 = F3 = 840N$.

- The center pin free body diagram:



The center pin diameter must be $D_1 = 32$ mm becaus, under the rules of design of stirrups by civil engineers when the diameter of the rebar is 8mm; the radius of the stirrup corners is 16 mm according to the standards.

For the small diameter (d) and (h) of the pin the slection gose under the loads which the pin will act and detailed below:

The maximum bending moment is at point B because there is a reduction of pin diameter; so, point B is a critical point.

$$\mathrm{M} = \mathrm{F1} * \mathrm{r1} + \mathrm{F2} * \mathrm{r2} + \mathrm{F3} * \mathrm{r3} \quad (13)$$

$$\mathrm{M} = \mathrm{F}(4 * 10^{-3} + 12 * 10^{-3} + 20 * 10^{-3}) \quad (14)$$

$$\mathrm{M} = 30.24\mathrm{N.m} \quad (15)$$

Assume the pin has a 28-mm diameter, d_1=28mm

Bending stress at point B:

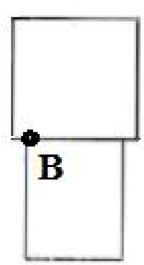


Figure 5.7: Point B for center pin

$$\sigma_x = \frac{32\ M}{\pi\ d^3} \tag{16}$$

$$\sigma_x = 14.0387\ \text{MPa} \tag{17}$$

The shear stress at point B

$$\tau_{xz} = \frac{3F}{A} \tag{18}$$

$$A = \pi\ r^2 \tag{19}$$

$$\tau_{xz} = 4.095\text{MPa} \tag{20}$$

At the critical point, the state of stress is a shown in following figure:

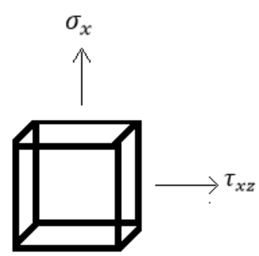


Figure5.8: Stress at point B

The principal stresses are:

$$\sigma_{A,B} = \frac{\sigma_x}{2} \frac{+}{-} \sqrt{(\frac{\sigma_x}{2})^2 + (\tau_{xz})^2} \tag{21}$$

$$\sigma_A = \ 15.145MPa \tag{22}$$

$$\sigma_B = -1.1063\ \text{MPa} \tag{23}$$

The von Mises stress σ'

$$\sigma' = \sqrt{\sigma_A{}^2 - \sigma_A\sigma_B + \sigma_B{}^2} = \tag{24}$$

$$\sigma' = 15.727 \text{ MPa} \tag{25}$$

Estimate the factor of safety using distortion-energy (DE) theory:

$$n = \frac{s_y}{\sigma'} = \frac{470}{15.727} = 29.88 \tag{26}$$

That means when the pin diameter is 28 mm, the design is on safe side.

Bearing stress:

Assume the depth of the pin in the disc h=30mm:

$$\sigma_b = \frac{3F}{A} \tag{27}$$

$$A = d * h \tag{28}$$

$$A = 0.028 * 0.03 = 0.84 * 10^{-3} m^2 \tag{29}$$

$$\sigma_b = 3 \text{ MPa} \tag{30}$$

Now find the factor of safety:

$$n = \frac{s_y}{\sigma_b} = \frac{470}{3} = 156.6 \tag{31}$$

Also, that means when the depth of the pin in the disc h = 30 mm, the design is on safe side, no threats come from bearing stresses.

1- Bending former pin

Mechanical calculation of this pin as same as in center pin mechanical design because both pins fall under the same influence of load.

- The bending former pin free body diagram:

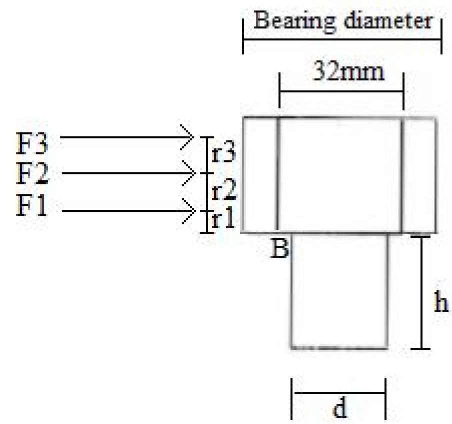
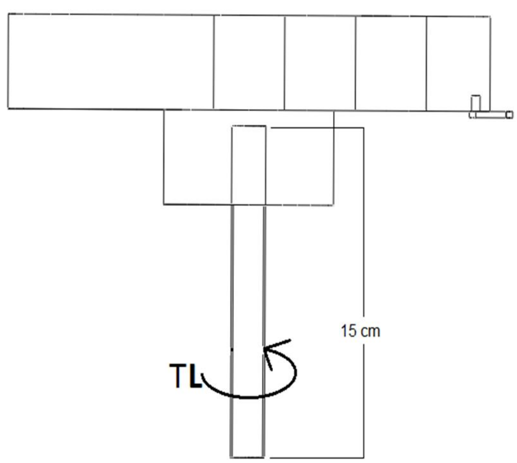
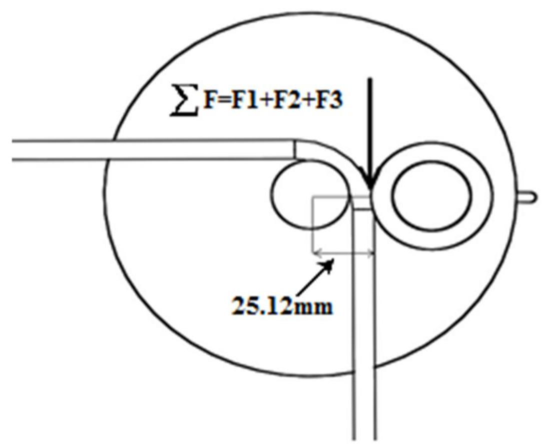


Figure 5.9: Bending former pin free body diagram

3- Shaft design





Calculate the load torque T_L [N·m]:

$$T_L = 3 * F * \left(9.12 + \frac{32}{2}\right) = 63.3024 \text{ N. M} \quad (32)$$

Assume shaft diameter D_3=40mm

Maximum shear stress τ:

$$\tau = \frac{16\ T_L}{\pi d^3} = 5.04\text{MPa} \tag{33}$$

Estimate the factor of safety using maximum shear stress theory:

$$n = \frac{\frac{s_y}{2}}{\tau} = \frac{235}{5.04} = 46.6. \tag{34}$$

That means when the shaft diameter is 40 mm, the design is on safe side.

Assume shaft length $L = 150mm$

Estimate the angle of twist

$$\phi = \frac{TL}{GJ} \tag{35}$$

$$\phi = \frac{63.3024 * 150 * 10^{-3}}{79.3 * 10^9 * 6.133 * 10^{-7}} \tag{36}$$

$$\phi = 0.0115\text{deg} \tag{37}$$

The angle of twist is small and ensure that no torsional vibration takes place during operation.

5.5 Belt drive selection

A belt is a loop of flexible material used to link two or more rotating shafts mechanically, most often parallel. Belts may be used as a source of motion, to transmit power efficiently, Belts are looped over pulleys and may have a twist between the pulleys, and the shafts need not be parallel.

In this project, belt drive used to transmit power and speed from bending motor to warm gearbox to achive the requird speed and toruqe for bending stage.

Based on the speed and power which will transmit from the motor to the gearbox also the diminsions bettwen them and refers to figure 5.11 , the best selection of v-belt is type ”A” . and his number is 58.

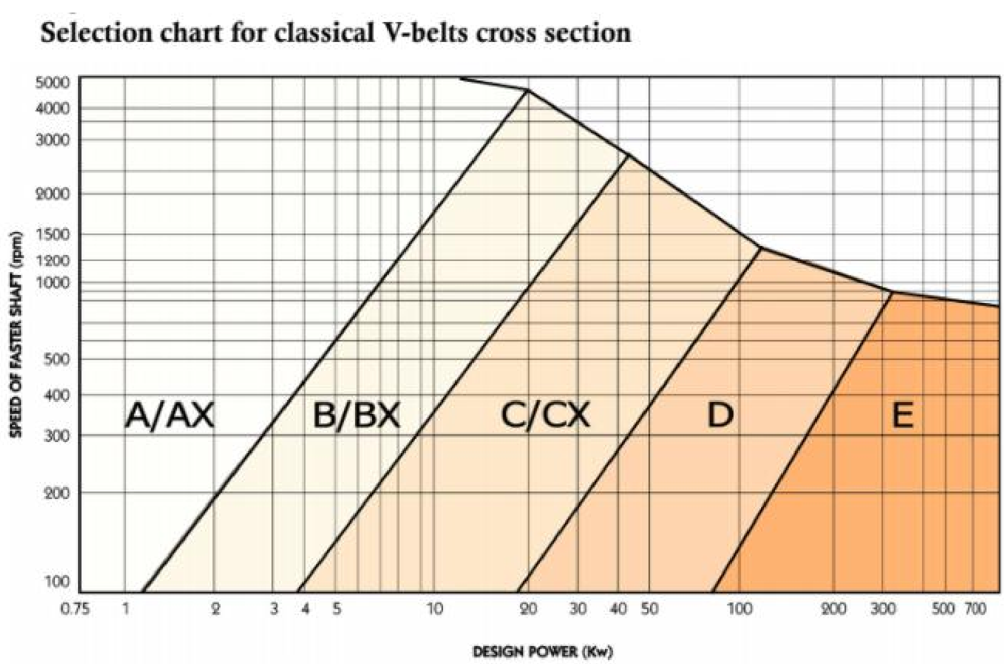


Figure 5.11: Selection chart for classical v-belt

For high-power requirements, two or more V-belts can be joined side-by-side in an arrangement called a multi-V, running on matching multi-groove sheaves. This is known as a multiple-V-belt drive.

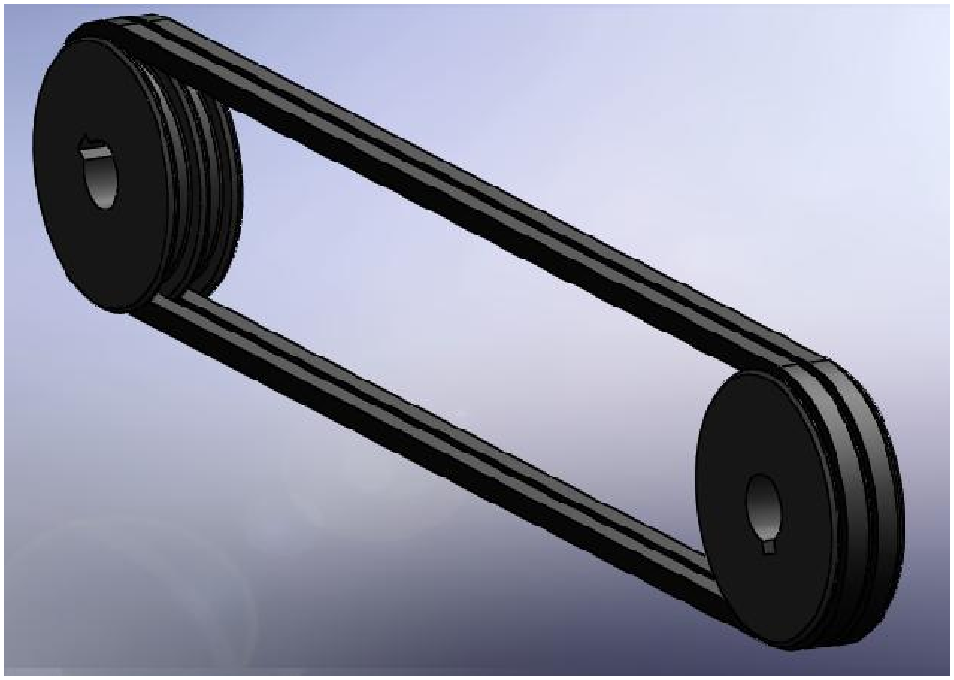


Figure 5.12: Pulley and belt design

5.6 Chain drive design

An advantage of chain drives over most belt drives is that the chain cannot slip on the sprocket, so the chain and sprocket provide a positive, non-slip drive, i.e. the chain cannot slip on the sprocket because the sprocket teeth prevent the chain from slipping.

The design of chain drive based on sprocket specifications:

1- The number of sprocket teeth $N = 25$
2- The pitch of chain p =10 mm
Calculated the pitch diameter:

$$D = \frac{P}{\sin\left(\frac{180}{N}\right)} = 12.6\text{mm} \tag{38}$$

- Chain length calculation:
To achieve high productivity, the chain must be long in order to contain the longest possible length of rebar.

The center distance is $C = 136cm$

The required chain length is calculated as follows:

$$\frac{L}{P} = 2\frac{C}{P} + \frac{N_2 + N_1}{2} + \frac{N_2 - N_1}{4\pi^2 \frac{C}{P}} \tag{39}$$

N_1: The number of drive sprocket teeth

N_2: The number of drive sprocket teeth

The required chain length $L = 297$ cm.

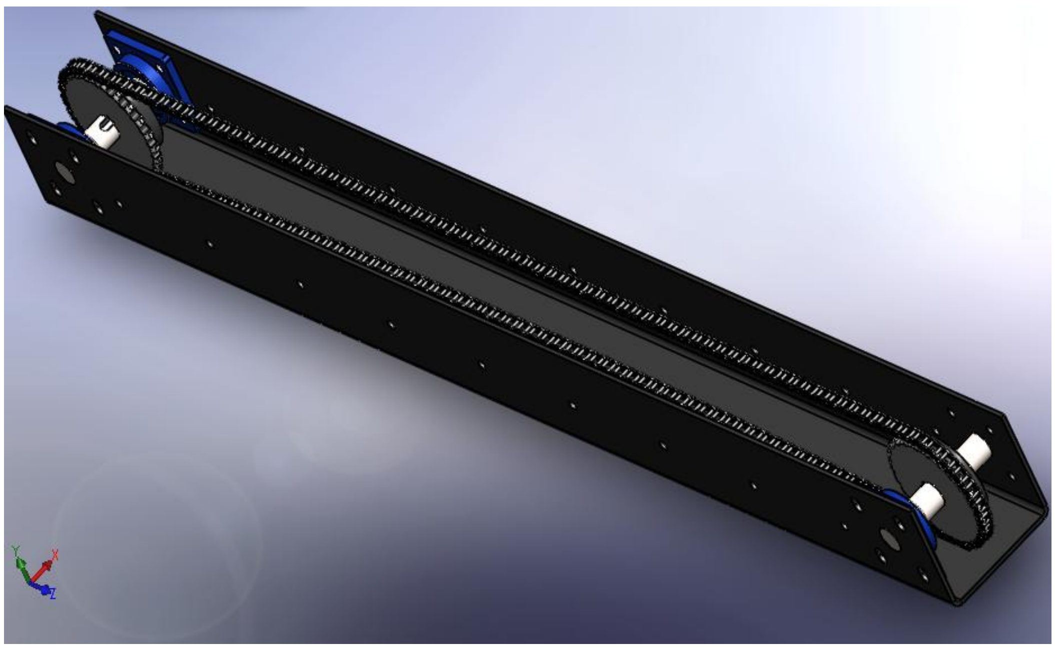


Figure 5.13:chain drive design

5.7 Selection of the Gear Ratio for bending motor

Assume the time required to form single corner is 1.5 -2 second, the bending former pin rotates 90 degrees clockwise and 90degrees counterclockwise in one second and that means the pin speed is half revolution per second, so the bending speed =15- 20rpm.

Because the rated speed for a 3-phase induction motor is 900 rpm, and the warm gearbox ratio which available is 1:50. Upon the motor speed and gear ratio the bending speed is 18rpm.

5.8 Selection of the Gear Ratio for feeder motor

Selection of the gearbox ratio depending on the available motor speed which is 1400-1500 rpm and the dimensions of sprocket and chain where:

P: The chain pitch and equals to 10mm.

N: The number of sprocket teeth equals to 25 T.

The driving sprocket speed given by

$$\text{sprocket speed}\left(\frac{\text{rev}}{\text{s}}\right) = \frac{\text{Chain speed}\left(\frac{\text{m}}{\text{s}}\right)}{\text{N p (m)}} \tag{40}$$

The required chain speed about 300 mm/s. so the sprocket speed is 72 rpm

Because the rated speed for a feeder motor is 1400 ~ 1500 rpm, the gear ratio is calculated as follows:

$$\text{i} = \frac{1500{\sim}1400}{72} = 19.44 \sim 20.8 \tag{43}$$

The gear ratio expected to be used ranges from 19 ~ 21, and worm gearbox can achieve this ratio and it suitable for this application.

The gear ratio which available is 20.

6

Chapter Six: Electrical Design

6.1 Introduction

Electrical design one of the main designs which interested in mechatronics design.

In this chapter electrical components and circuits design will be describe.

6.2 Motors

An electric motor is an electrical machine that converts electrical energy into mechanical energy. In this section electrical motors specifications which includes AC motors and DC motors will be explained, where motors selection was based on the application of each motor:

1- Bending AC motor:
   Is the motor which actuate bending process where this motor connected with bending gear box and has the following specifications, Table 6.1.

Table 6.1: Bending motor specification

Specifications	**Value**	**Unit**
Power	3	Horse Power (HP)
Rated Voltage Y/Δ	380/220	Volt
Frequency	50	Hertz (Hz)
Rated current Y/Δ	9.86/5.7	Ampere
No load speed	900	r/min

2- Feeding AC motor:
   Is the motor which moving feeding system through worm gear box and has the following specifications, Table 6.2.

Table 6.2 Feeding motor specification

Specifications	**Value**	**Unit**
Power	0.5	Horse Power (HP)
Rated Voltage Y/Δ	380/220	Volt
Frequency	50	Hertz (Hz)
Rated current Y/Δ	1.27/2.2	Ampere
No load speed	1380	r/min

3- Gripping DC motor:

The electrical gripping motor is a permanganic rotary electrical motor. A worm gear machined on the armature shaft drives the output shaft and gear through an idler gear and shaft, although it needs DC supply but this motor achieves the application of gripping mechanism in addition to availability and price. And has the following specifications, Table 6.3.

Table 6.3: Gripping motor specification

Specifications	**Value**	**Unit**
Power	50	Watt
Rated Voltage	12/24	Volt
No load current	2.0/2.5	Ampere
No load current	6.5/7.5	Ampere
No load speed	40/60±5	r/min

4- Plate's DC motor:

Plate's motor is brush-commutated gearmotor sintered spur gear Figure 6.2, achieved application needs.
Table 6.4 shows motor specifications.

Table 6.4: plate's motor specification

Specifications	**Value**	**Unit**
Rated Voltage	19.1	Volt
No load current	0.20	Ampere
No load current	4.06	Ampere
No load speed	6000	r/min
Gear ratio	19.7:1	——

6.3 Sensors

A sensor is a device that detects and responds to some type of input from the physical environment.

In this project two types of sensors used:

1- Rotary encoder:
A rotary encoder, also called a shaft encoder, is an electro-mechanical device that converts the angular position of a shaft to an analog or digital signal. In this project this sensor which connected with feeding motor gear box used to count the linear motion of the feeder to detect the dimensions of stirrups Figure 6.3.

Encoder specifications Table 6.5:

Table 6.5: encoder specification

E50S	8 —	600 —	3 —	24
Series	Shaft diameter	Pulse/1Revolution	Output phase	Power supply
Diameter ø50mm, shaft type	ø8mm	600 ppr	3: A, B, Z	24:12-24VDC ±5%

2- Limit switches & Micro limit switches:

Limit switch sensor is a switch operated by the motion of a machine parts or presence of an object, where this sensor used in several positions in the machine as shown in Figure 6.4:

- Bending process: to detect the rotation of the disc.
- Feeding process: at the beginning of feeder and end of it.
- Plate mechanism: plate up and down process.
- Gripping mechanism: closed and opining process.

6.4 Switches & Controlled switches

- Push-button switches

  Push-button switch is one of the most important parts which used in automatic control and its function to turn on or off some functions, as in this project push-button used for start the machine process and stop it Figure 6.5.

- Contactors

  A contactor is an electrically controlled switch used for switching an electrical power circuit. A contactor is typically controlled by a circuit which has a much lower power level than the switched circuit Figure 6.6.

  Contactors come in many forms with varying capacities and features. Unlike a circuit breaker, a contractor is not intended to interrupt a short circuit current. Contactors range from those having a breaking current of several amperes to thousands of amperes and 24 V DC to many kilovolts.

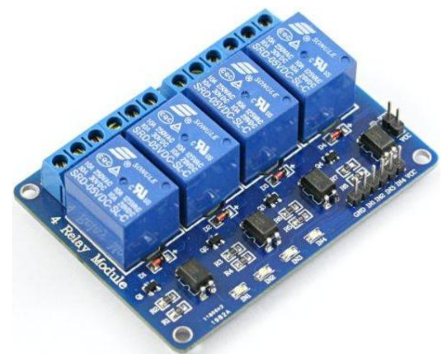
  Contactors are used to control electric motors, lighting, heating, and other electrical loads.

  In this project contactors used to control the direction of bending motor CW or CCW. They must be 3phase contactor with 6A operation current which equals to Bending motor amperes at star connection.

- Relays

  A relay is an electrically operated switch used an electromagnet to mechanically operate a switch. Relays are used where it is necessary to control a circuit by a separate low-power signal, or where several circuits must be controlled by one signal.

  In this project relays used to control the direction for plate’s motor and gripping motor, and they operate at 5v Figure 6.7.



6.5 Variable Frequency Drive (VFD)

variable-frequency drive (VFD); also termed variable speed drive, or “inverter” drive is a type of adjustable-speed drive used in electro-mechanical drive systems to control AC motor speed and torque by varying motor input frequency and voltage.

VFD shown in Figure 6.8 used for this machine as an interface between Programmable Logic Control(PLC) and the feeder’s motor and get a soft starting for motor.

Figure 6.8: Variable frequency drive

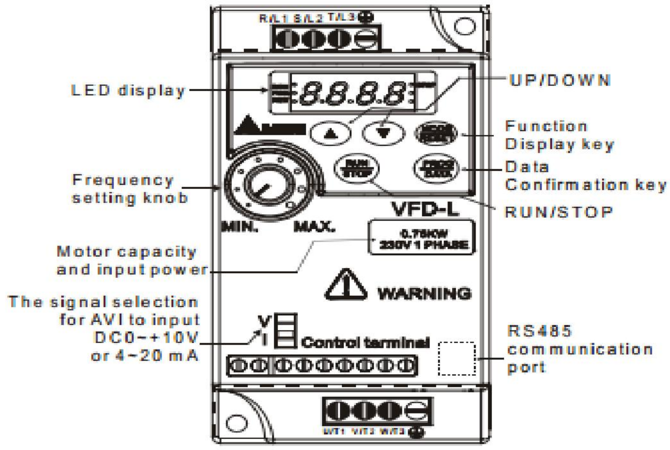


Figure 6.9: Main circuit diagram of delta VFD

6.6 Human Machine Interface (HMI)

Human Machine Interface (HMI) is considered an interface that allows humans to interact with the machine, in this project the HMI which used is a touch screen Figure 6.10, used to enter the dimensions of stirrups and for other functions such as: start, stop and start cycle.

Figure 6.10: Touch screen

6.7 Electrical protection

Power-system protection is a branch of electrical power engineering that deals with the protection of electrical power systems from faults through the isolation of faulted parts from the rest of the electrical network. The devices that are used to protect the power systems from faults are called protection devices which includes in this project: The devices that are used to protect the power systems from faults are called protection devices.

Protection Devices:

1- Circuit breaker:

A circuit breaker is an automatically operated electrical switch designed to protect an electrical circuit from damage caused by excess current from an overload or short circuit, shown in Figure 6.11 and Figure 6.12.

Figure 6.11: single phase circuit breaker

Figure 6.12: Three phase circuit breaker

2- Overload:

Overload protection is a protection against a running overcurrent that would cause overheating of the protected equipment Figure 6.13.

The operation current of overload determined depending on the motor current which appears in its name plate.

Figure 6.13: Overload circuit breaker

3- Fuses:

Is an electrical safety device operating to provide overcurrent protection of an electrical component or circuits, its essential component is a metal wire or strip that melts when too much current flows through it, thereby interrupting the current. In this project fuses used to protect DC motors from overcurrent, Figure 6.14.

Figure 6.14: Fuse

4- Earth Leakage Circuit Breaker (ELCB)

An ECLB is one kind of safety device used for installing an electrical device with high earth impedance to avoid shock. These devices identify small stray voltages of the electrical device on the metal enclosures and intrude the circuit if a dangerous voltage is identified. The main purpose of Earth leakage circuit breaker (ECLB) is to stop damage to humans due to electric shock, Figure 6.16.

Figure 6.15: Earth leakage circuit breaker

5- Emergency stop:

Emergency stop is a normally closed switch used to stop the machine process in emergency situations to protect human and machine parts from any danger or damage, Figure 6.16.

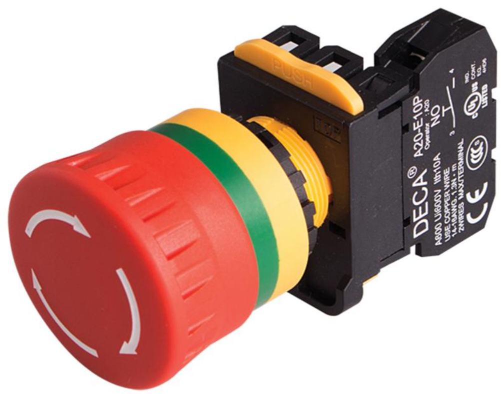
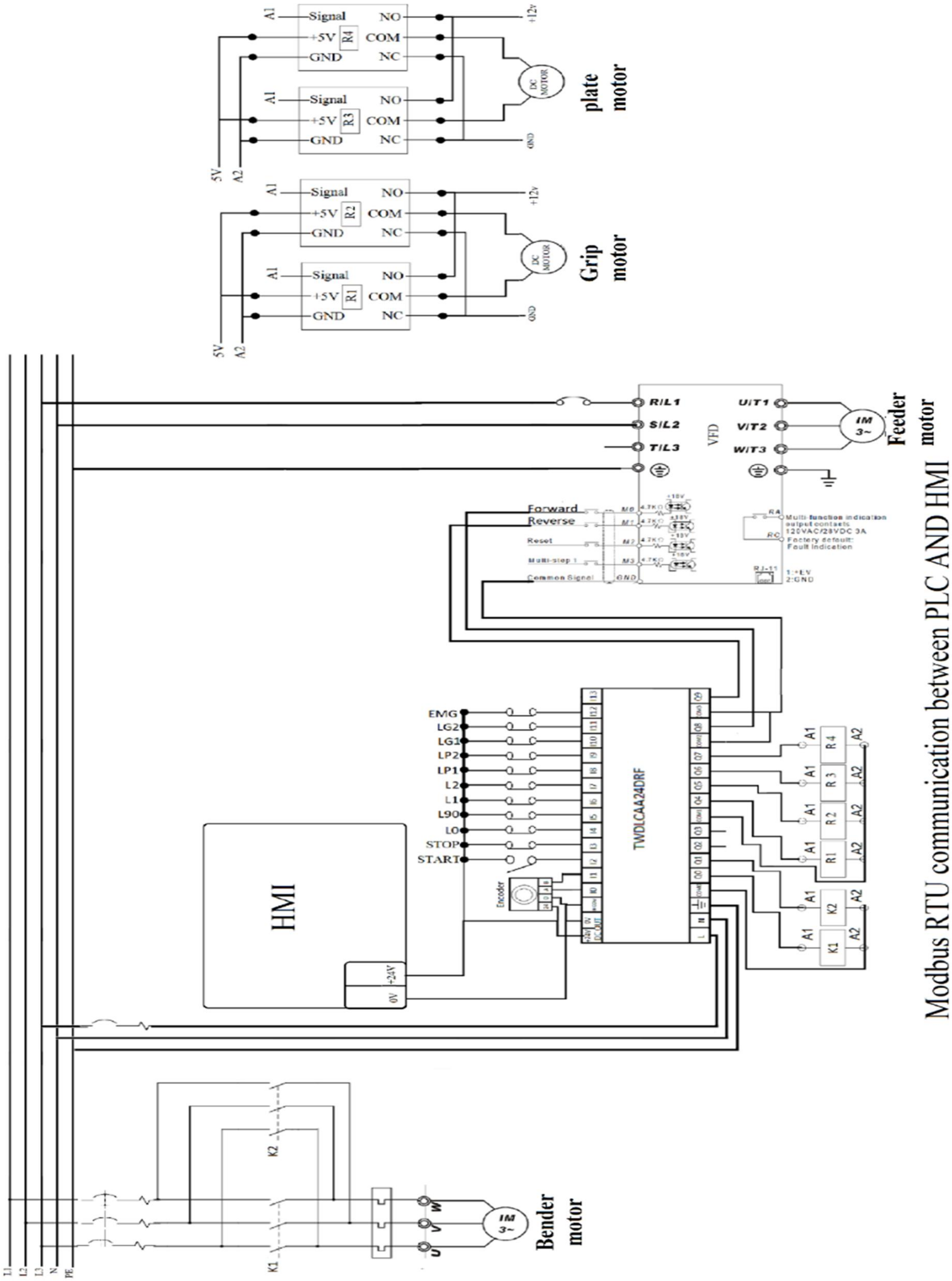


Figure 6.16: Emergency stop

6.8 Wiring diagram (power and control circuit)



7

Chapter Seven: PLC Programing

7.1 Introduction

As it has been mentioned before the machine is fully automated and the forming process is sequentially, this can be performed by using PLC.

Programmable Logic Controller (PLC) is a special computer device used in industrial control systems. Due to its robust construction, exceptional functional features like sequential control, counters and timers, easy of programming, reliable controlling capabilities and easy of hardware usage.

The programmable logic controller chosen to control the machine instead of the microcontroller because it works at 220 volts, where the microcontroller works only with 5 volts, a comparison between plc and Microcontroller is shown in the table 7_1.

Table 7.1: PLC vs Microcontroller

	Plc	Microcontroller
Easy in Programming	✓	
Less initial cost		✓
Work at 220V	✓	
Large capacity I/OS	✓	
The most powerful industrial applications	✓	
Fast response		✓

7.2 PLC specifications

A PLC is used for continuously monitoring the input values from sensors and produces the outputs for the operation of actuators based on the program.

In the controller design of the machine it is desirable to use a PLC with 13 inputs and 8 outputs mentioned in table 7.2 and table 7.3 and the PLC connection shown in the figure 7.1.

Table 7.2: Logic allocation input tables

Input	Symbol	Type	Logic allocation	Address	
				PLC	HMI
Pulse Phase B			Count pulse	I0.0	
Pulse Phase A				I0.1	
Start	START	NO set on	After insert dimension, START =1, Operation is run	I0.2	%M0
Stop	STOP	NC	Stop=0, Operation is stop after complete of the current cycle	I0.3	
Limit switch 1	L0	NC	L0=0, the bender in position zero deg	I0.4	
Limit switch 2	L90	NC	L90=0, the bender in position 90deg	I0.5	
Limit switch 3	L1	NC	L1=0, the grip in the start feeder	I0.6	
Limit switch 4	L2	NC	L2=0, the grip in the end feeder	I0.7	
Limit switch 5	LP1	NC	LP1=0, the plate is open	I0.8	
Limit switch 6	LP2	NC	LP2=0, the plate is close	I0.9	
Limit switch 7	LG1	NC	LG1=0, the grip is close	I0.10	
Limit switch 8	LG2	NC	LG2=0, the grip is open	I0.11	
Emergency switch	EMG	NC	EMG=0, Turn off all process	I0.12	
Start cycle	START CYCLE	Set on	After insert rebar, START CYCLE =1, start new cycle		%M1
Demission A	A	Numeric	Dimensions of the stirrup, the worker enters them		%MW0
Dimensions B	B	Numeric			%MW1

Table 7.3: Logic allocation output table

Output	Symbol	Logic allocation	Address
Bending motor	MB1	MB1=1, Bending motor running CW	Q0.0
	MB2	MB2=1, Bending motor running CCW	Q0.1
Gripping motor	MG1	MG1=1, Griping motor running CW	Q0.4
	MG2	MG2=1, Griping motor running CCW	Q0.5
Plate's motor	MP1	MP1=1, Plate's motor running CW	Q0.6
	MP2	MP2=1, Plate's motor running CCW	Q0.7
Feeding motor	MF1	MF1=1, Feeding motor running CW	Q0.8
	MF2	MF2=1, Feeding motor running CCW	Q0.9

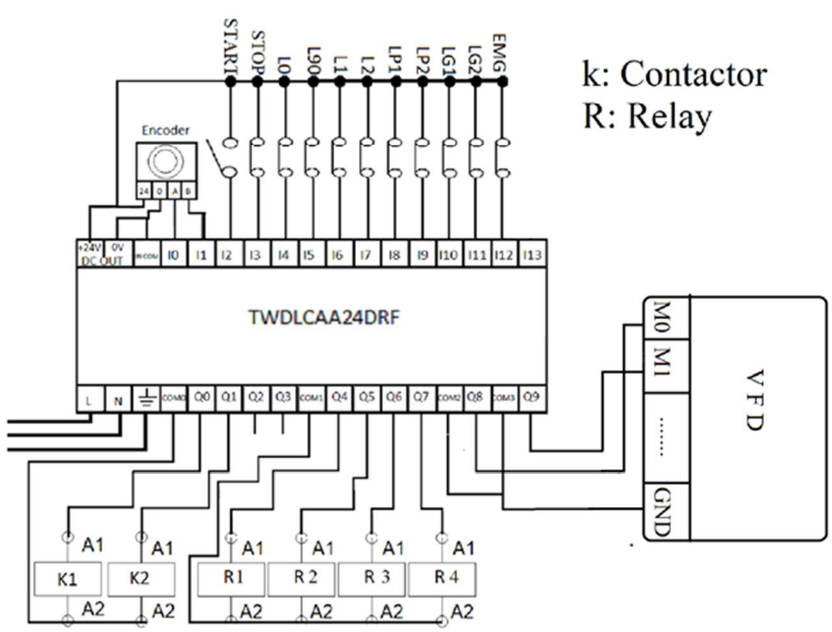
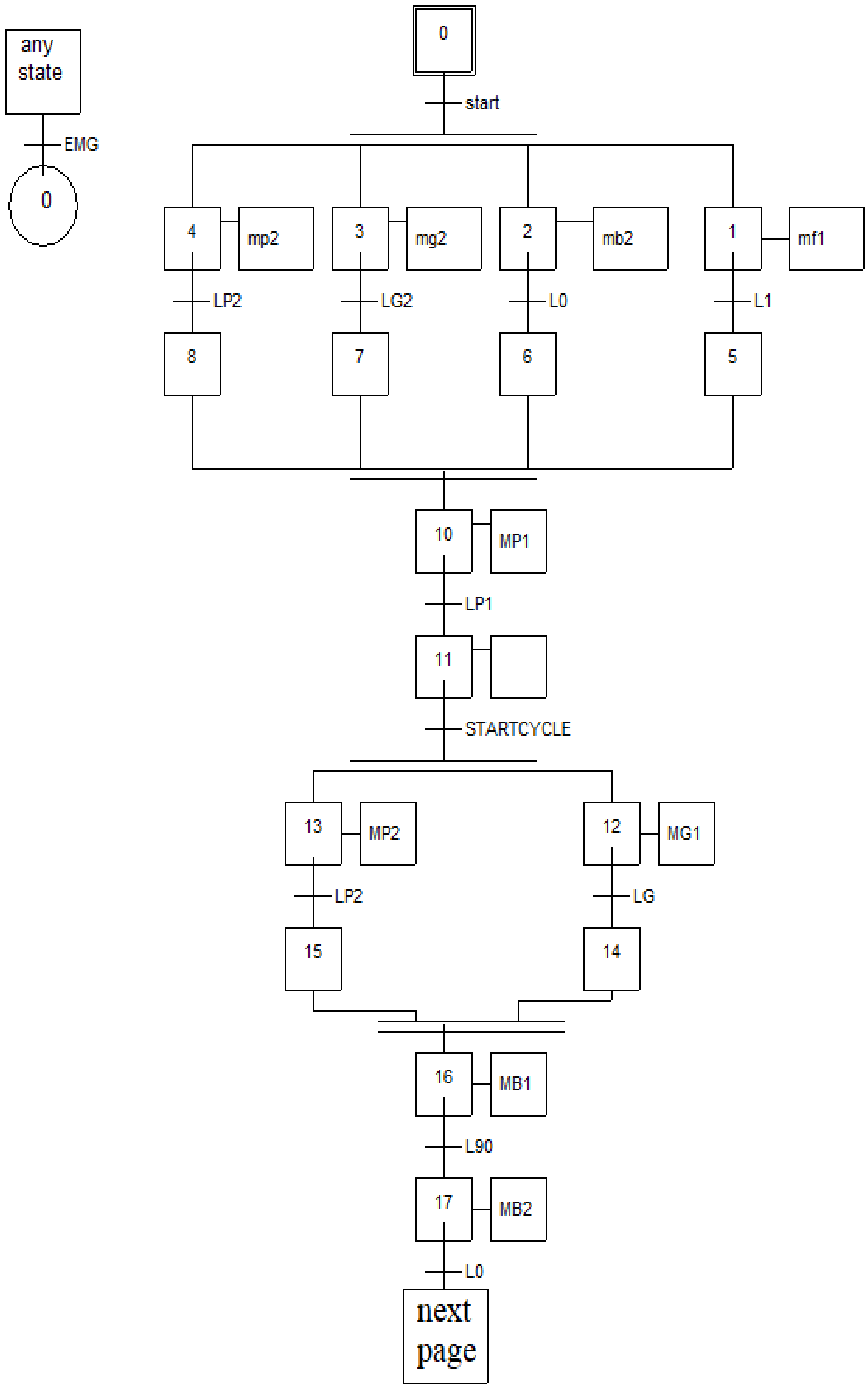


Figure 7.1: PLC Connection

7.3 State graph

State graph shown in following figure represent working principle.



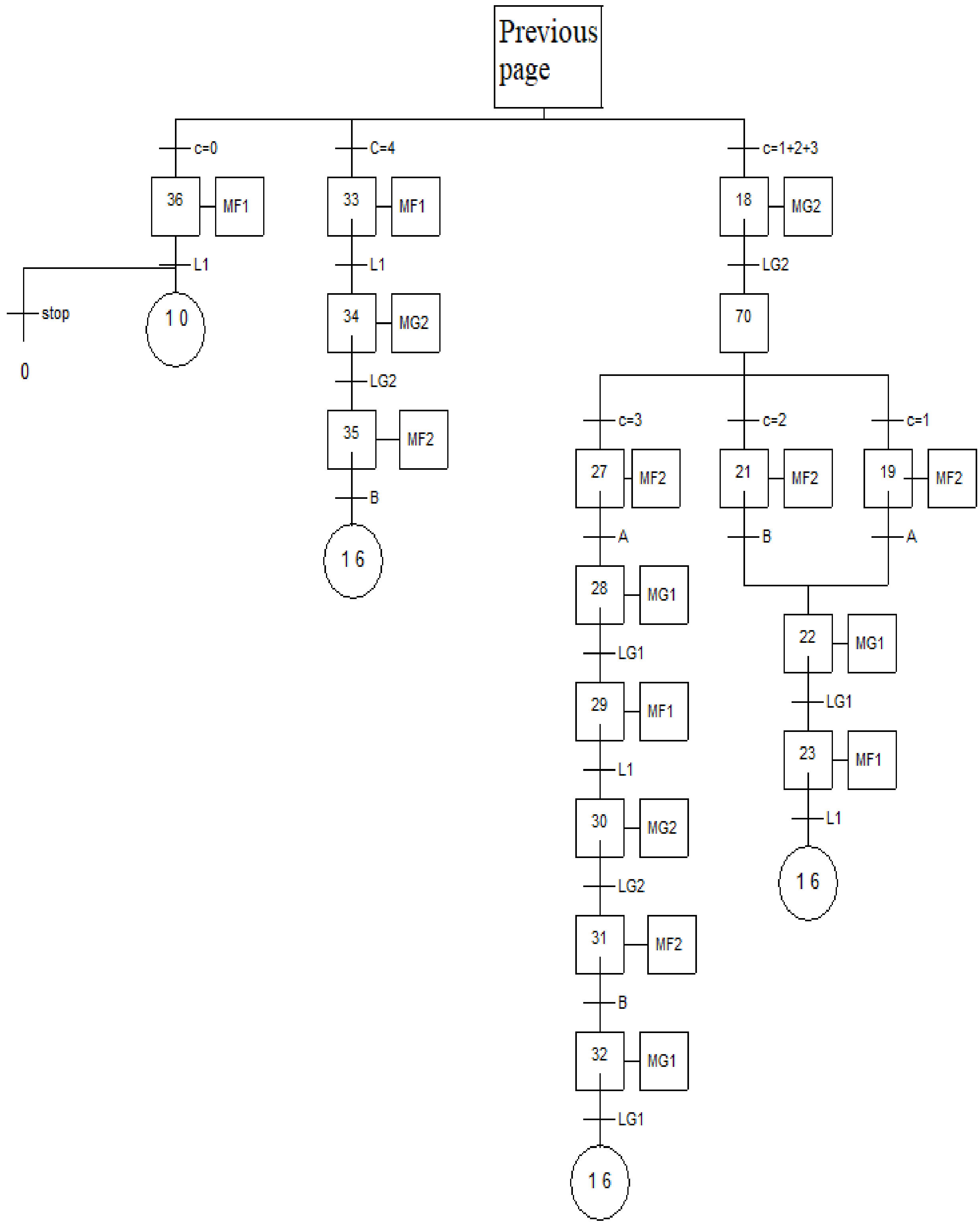


Figure 7.2: State graph

- For ladder language Appendix A “Programing code” page82.

8

Chapter eight: Results and Recommendations

8.1 Introduction

By the end of the project, this chapter provides results of it in addition to recommendations proposed from project team to enhance the project and develop the local market.

8.2 Results

The main advantage of graduation project is improving graduates students skills includes: technical skills, teamwork. As for experimental results of Automatic Rebar Bending Machine to Form Rectangular Stirrups were as follow:

1- Bending stage: for this stage of machine it can bend more than 3 rebars together until 6 rebars.
2- The machine product rate for one cycle with 3 rebars to form 20X40cm was between 10-15 seconds.
3- The machine can bend rebars regardless to their lengths where the machine programing method built to deal with long rebars even their length greater than feeding system.
4- Project idea was popular in local market where the machine increased production rate of rectangular stirrups accurate in addition to improving safety level and easy to use.

Figure 8.1: Final product

The automatic rebar bending machine to form rectangular stirrups shown in following figure.

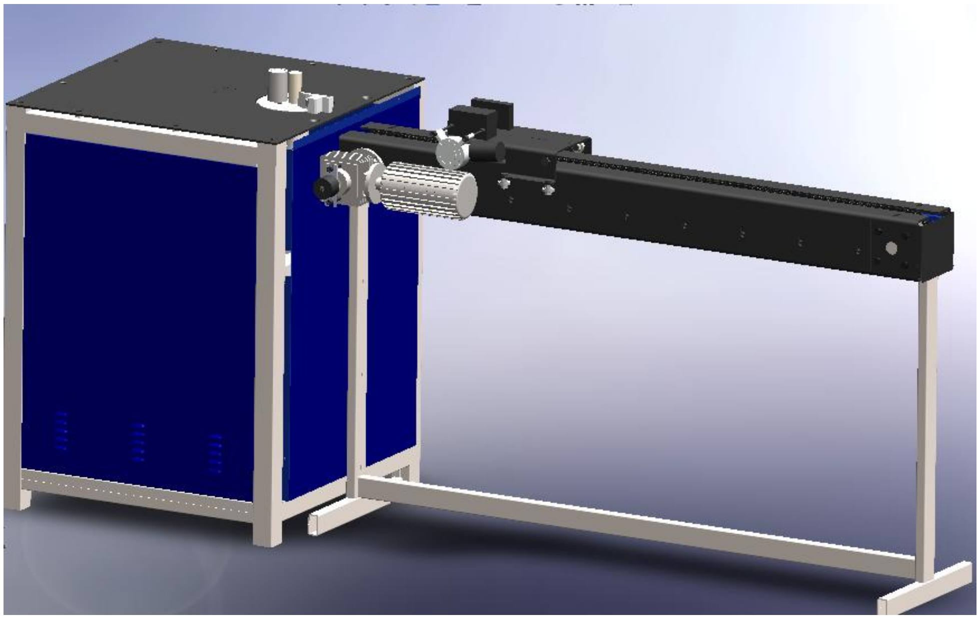


Figure 8.2: The final machine

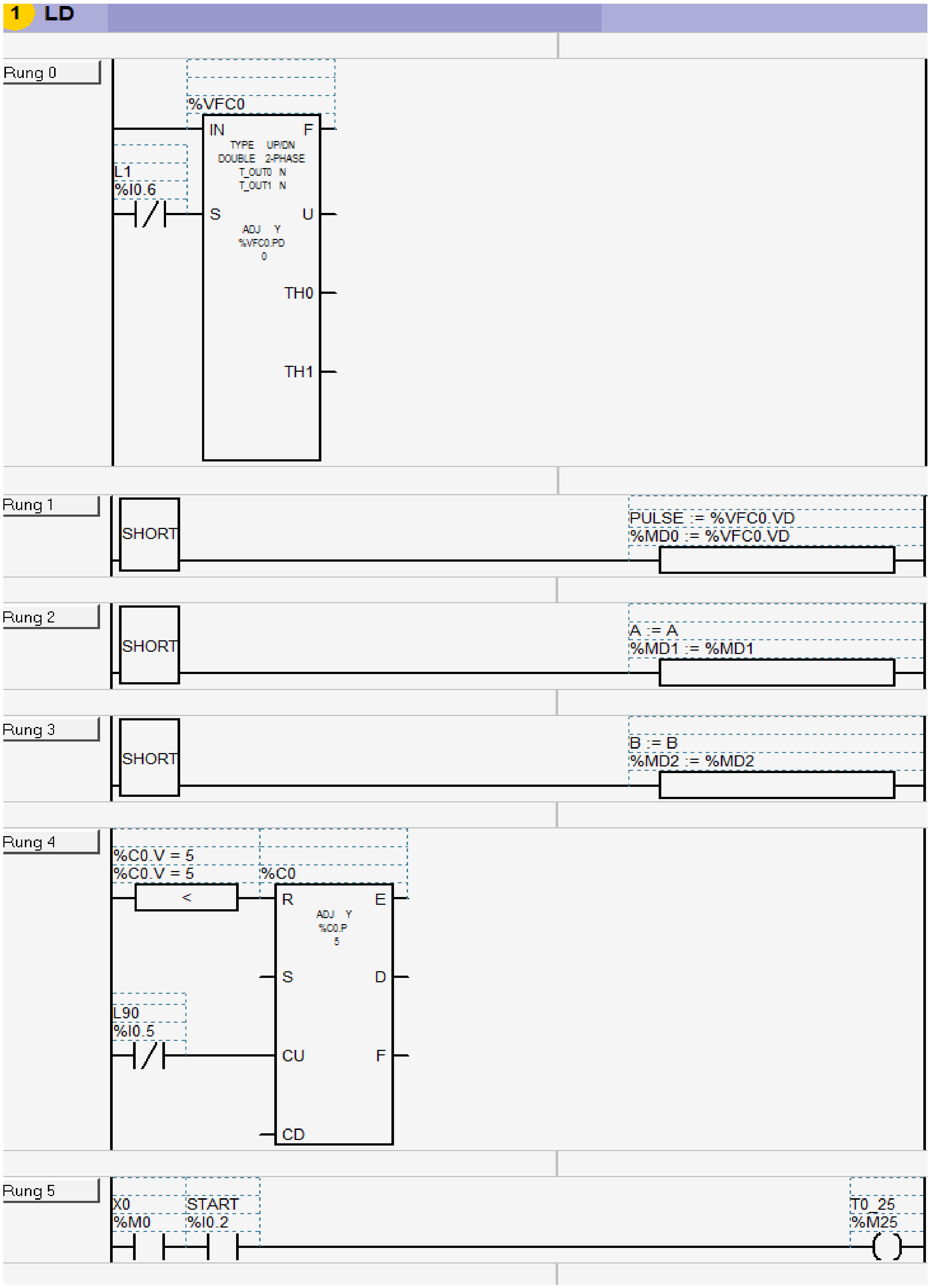
8.3 Recommendations

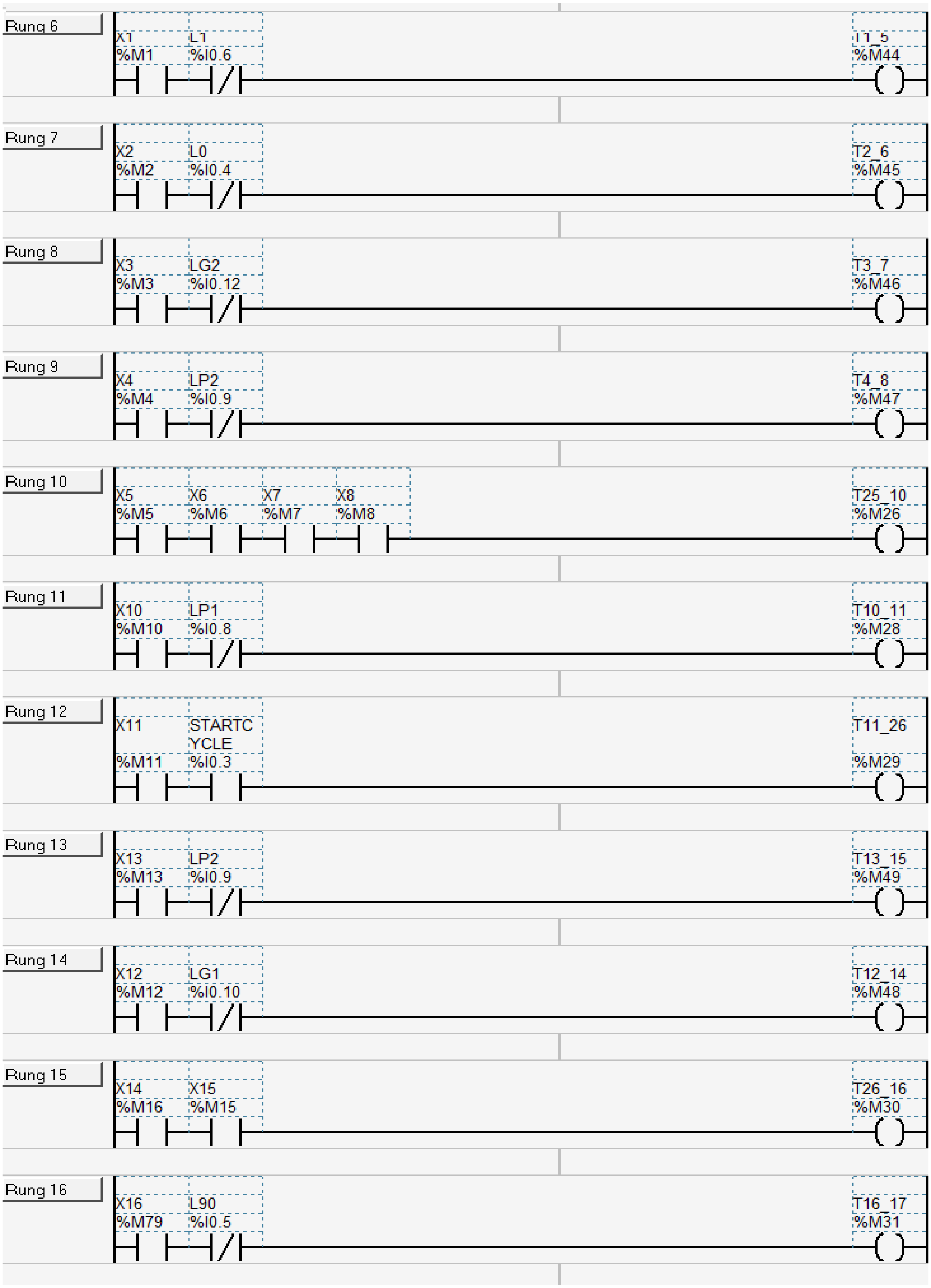
The purpose of any project is continuity and develop the project, in this section recommendations suggested for this aim specially for those whom will work on the project in future, includes:

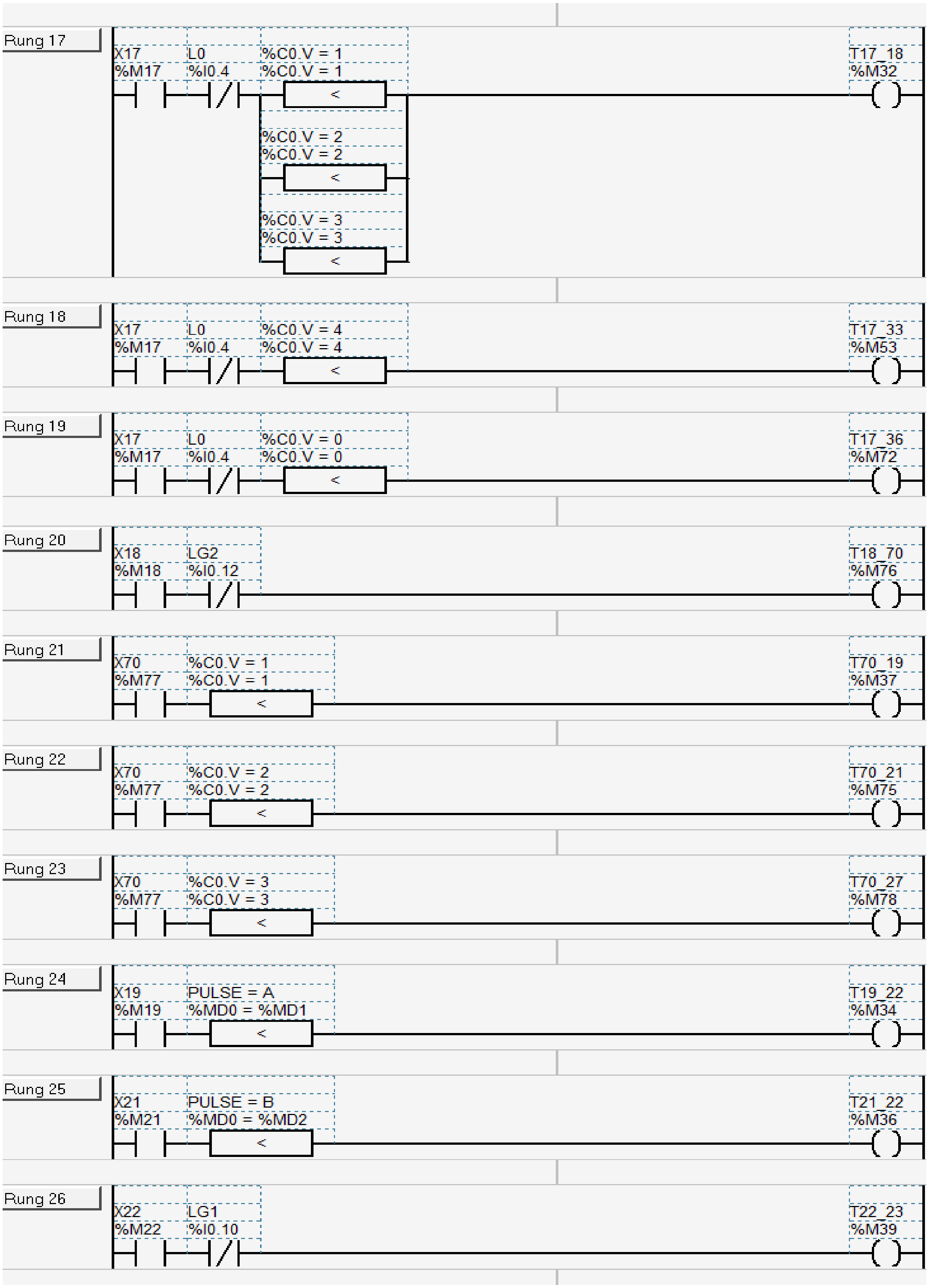
1- Adding a proximity sensor to detect if there is rebars or not at bending mechanism.
2- Developing machine capacity to form stirrups with different radius such that 10mm,16mm and 32mm, and forming several types of stirrups.
3- Enhance machine safety by adding photo sensor around the machine.
4- Insert cutting mechanism for long rebars even for roll feeding system instead of rebars.
5- The university administration financially supported graduation projects, this support must be provided at the beginning of the project work, to enable students implementing their projects according to the time plan, and to test them at the proper time.
6- The university should provide the proper toolsets, which enable the student to assemble his project and to test it which will get benefit of experiences in the university.

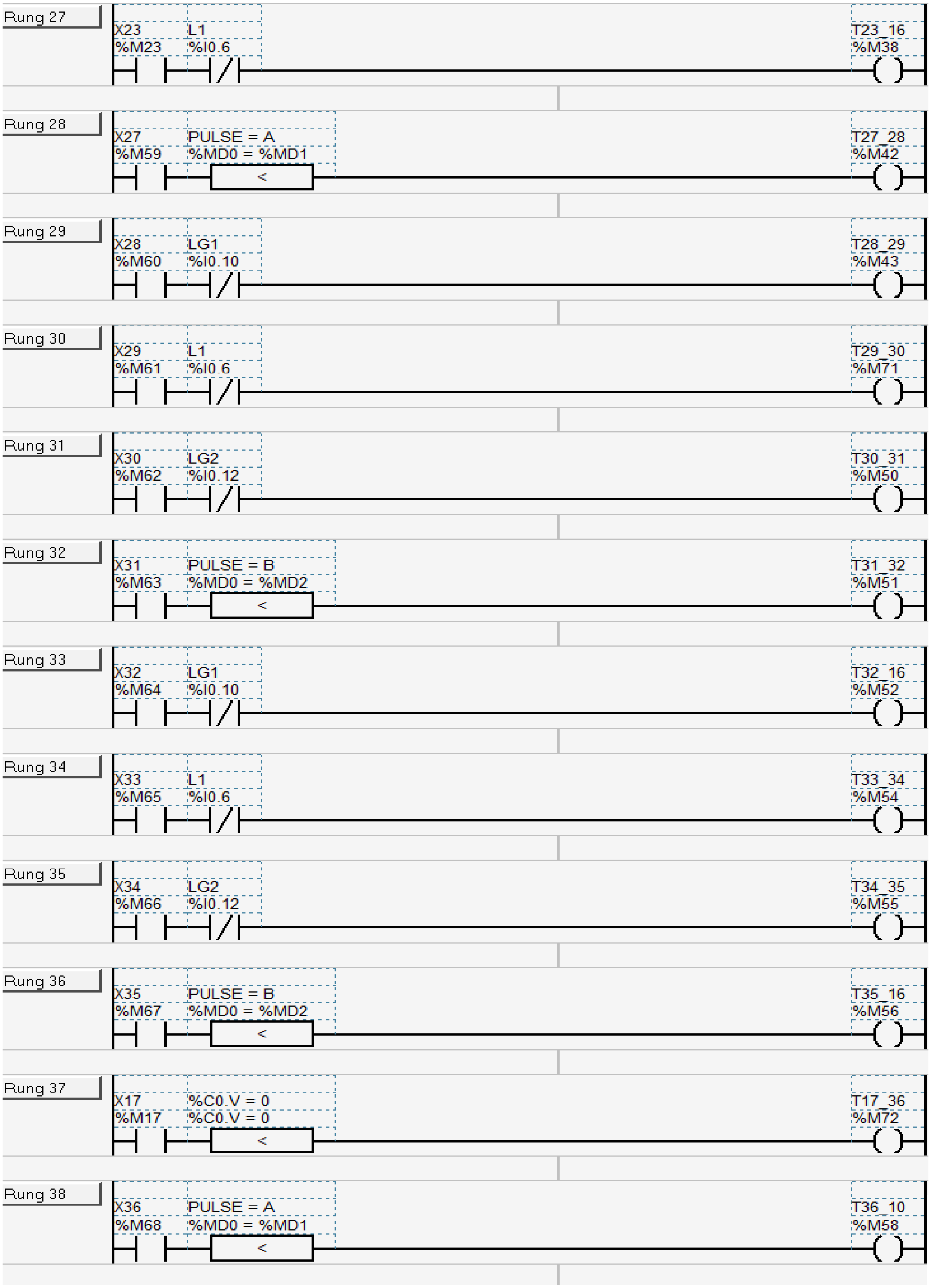
Appendix A

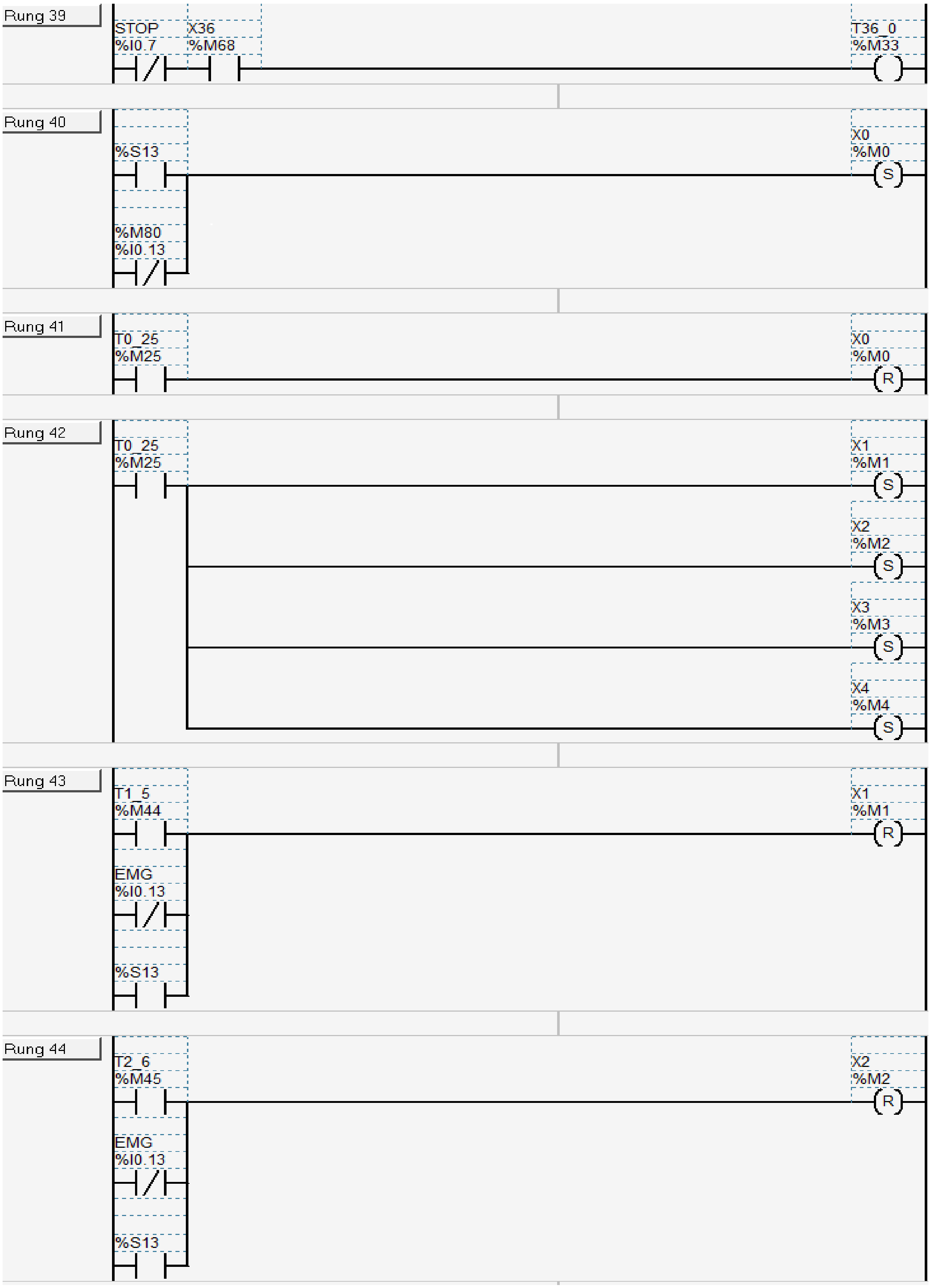
Programming Code

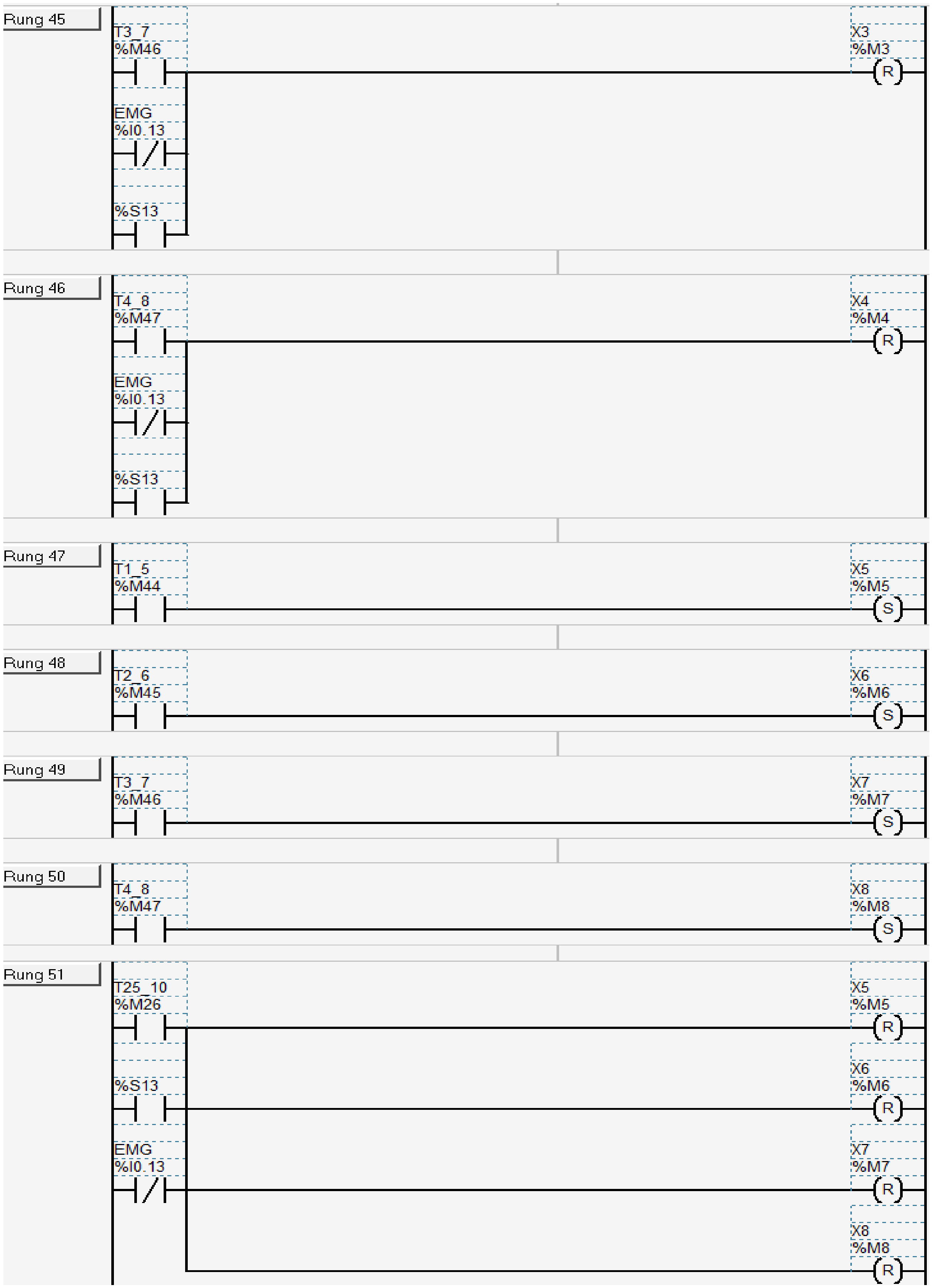

1 LD
Rung 0
%VFC0
IN
F
TYPE UP/DN
DOUBLE 2-PHASE
T_OUT0 N
T_OUT1 N
L1
%I0.6
S
U
ADJ Y
%VFC0.PD
0
TH0
TH1
Rung 1
SHORT
PULSE := %VFC0.VD
%MD0 := %VFC0.VD
Rung 2
SHORT
A := A
%MD1 := %MD1
Rung 3
SHORT
B := B
%MD2 := %MD2
Rung 4
%C0.V = 5
%C0.V = 5
<
%C0
R
E
ADJ Y
%C0.P
5
S
D
L90
%I0.5
CU
F
CD
Rung 5
X0
%M0
START
%I0.2
T0_25
%M25


Rung 6
X1 %M1
L1 %I0.6
T1_5 %M44
Rung 7
X2 %M2
L0 %I0.4
T2_6 %M45
Rung 8
X3 %M3
LG2 %I0.12
T3_7 %M46
Rung 9
X4 %M4
LP2 %I0.9
T4_8 %M47
Rung 10
X5 %M5
X6 %M6
X7 %M7
X8 %M8
T25_10 %M26
Rung 11
X10 %M10
LP1 %I0.8
T10_11 %M28
Rung 12
X11 %M11
STARTC YCLE %I0.3
T11_26 %M29
Rung 13
X13 %M13
LP2 %I0.9
T13_15 %M49
Rung 14
X12 %M12
LG1 %I0.10
T12_14 %M48
Rung 15
X14 %M16
X15 %M15
T26_16 %M30
Rung 16
X16 %M79
L90 %I0.5
T16_17 %M31

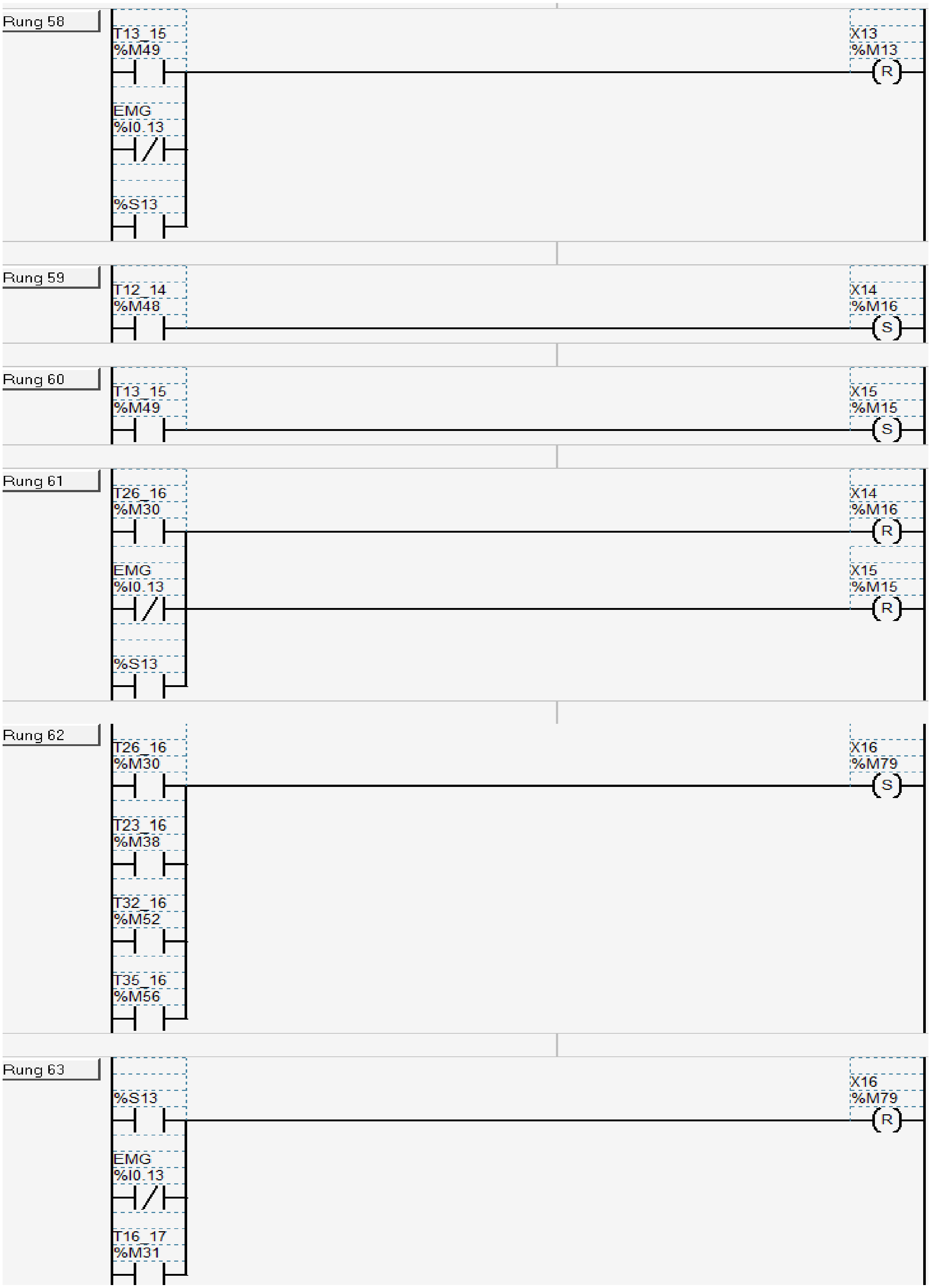

Rung 17
X17
%M17
L0
%I0.4
%C0.V = 1
%C0.V = 1
<
%C0.V = 2
%C0.V = 2
<
%C0.V = 3
%C0.V = 3
<
T17_18
%M32
Rung 18
X17
%M17
L0
%I0.4
%C0.V = 4
%C0.V = 4
<
T17_33
%M53
Rung 19
X17
%M17
L0
%I0.4
%C0.V = 0
%C0.V = 0
<
T17_36
%M72
Rung 20
X18
%M18
LG2
%I0.12
T18_70
%M76
Rung 21
X70
%M77
%C0.V = 1
%C0.V = 1
<
T70_19
%M37
Rung 22
X70
%M77
%C0.V = 2
%C0.V = 2
<
T70_21
%M75
Rung 23
X70
%M77
%C0.V = 3
%C0.V = 3
<
T70_27
%M78
Rung 24
X19
%M19
PULSE = A
%MD0 = %MD1
<
T19_22
%M34
Rung 25
X21
%M21
PULSE = B
%MD0 = %MD2
<
T21_22
%M36
Rung 26
X22
%M22
LG1
%I0.10
T22_23
%M39


Rung 27
X23
%M23
L1
%I0.6
T23_16
%M38
Rung 28
X27
%M59
PULSE = A
%MD0 = %MD1
<
T27_28
%M42
Rung 29
X28
%M60
LG1
%I0.10
T28_29
%M43
Rung 30
X29
%M61
L1
%I0.6
T29_30
%M71
Rung 31
X30
%M62
LG2
%I0.12
T30_31
%M50
Rung 32
X31
%M63
PULSE = B
%MD0 = %MD2
<
T31_32
%M51
Rung 33
X32
%M64
LG1
%I0.10
T32_16
%M52
Rung 34
X33
%M65
L1
%I0.6
T33_34
%M54
Rung 35
X34
%M66
LG2
%I0.12
T34_35
%M55
Rung 36
X35
%M67
PULSE = B
%MD0 = %MD2
<
T35_16
%M56
Rung 37
X17
%M17
%C0.V = 0
%C0.V = 0
<
T17_36
%M72
Rung 38
X36
%M68
PULSE = A
%MD0 = %MD1
<
T36_10
%M58


Rung 39
STOP
%I0.7
X36
%M68
T36_0
%M33
Rung 40
%S13
%M80
%I0.13
X0
%M0
S
Rung 41
T0_25
%M25
X0
%M0
R
Rung 42
T0_25
%M25
X1
%M1
S
X2
%M2
S
X3
%M3
S
X4
%M4
S
Rung 43
T1_5
%M44
EMG
%I0.13
%S13
X1
%M1
R
Rung 44
T2_6
%M45
EMG
%I0.13
%S13
X2
%M2
R


Rung 45
T3_7
%M46
EMG
%I0.13
%S13
X3
%M3
R
Rung 46
T4_8
%M47
EMG
%I0.13
%S13
X4
%M4
R
Rung 47
T1_5
%M44
X5
%M5
S
Rung 48
T2_6
%M45
X6
%M6
S
Rung 49
T3_7
%M46
X7
%M7
S
Rung 50
T4_8
%M47
X8
%M8
S
Rung 51
T25_10
%M26
%S13
EMG
%I0.13
X5
%M5
R
X6
%M6
R
X7
%M7
R
X8
%M8
R

Rung 52
T25_10
%M26
T36_10
%M58
X10
%M10
S
Rung 53
T10_11
%M28
EMG
%I0.13
%S13
X10
%M10
R
Rung 54
T10_11
%M28
X11
%M11
S
Rung 55
T11_26
%M29
EMG
%I0.13
%S13
X11
%M11
R
Rung 56
T11_26
%M29
X12
%M12
S
X13
%M13
S
Rung 57
T12_14
%M48
EMG
%I0.13
%S13
X12
%M12
R


Rung 58
T13_15
%M49
EMG
%I0.13
%S13
X13
%M13
R
Rung 59
T12_14
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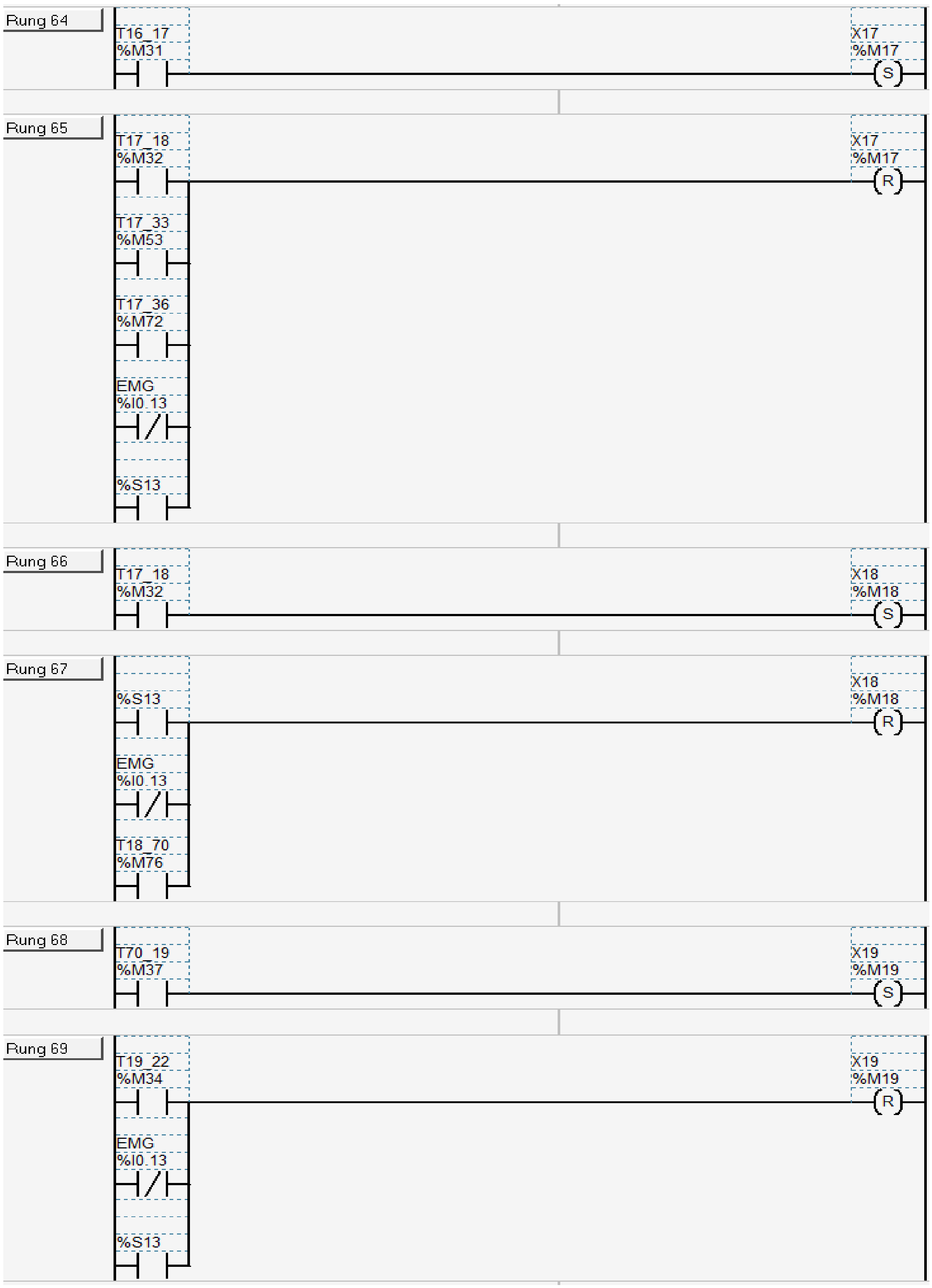
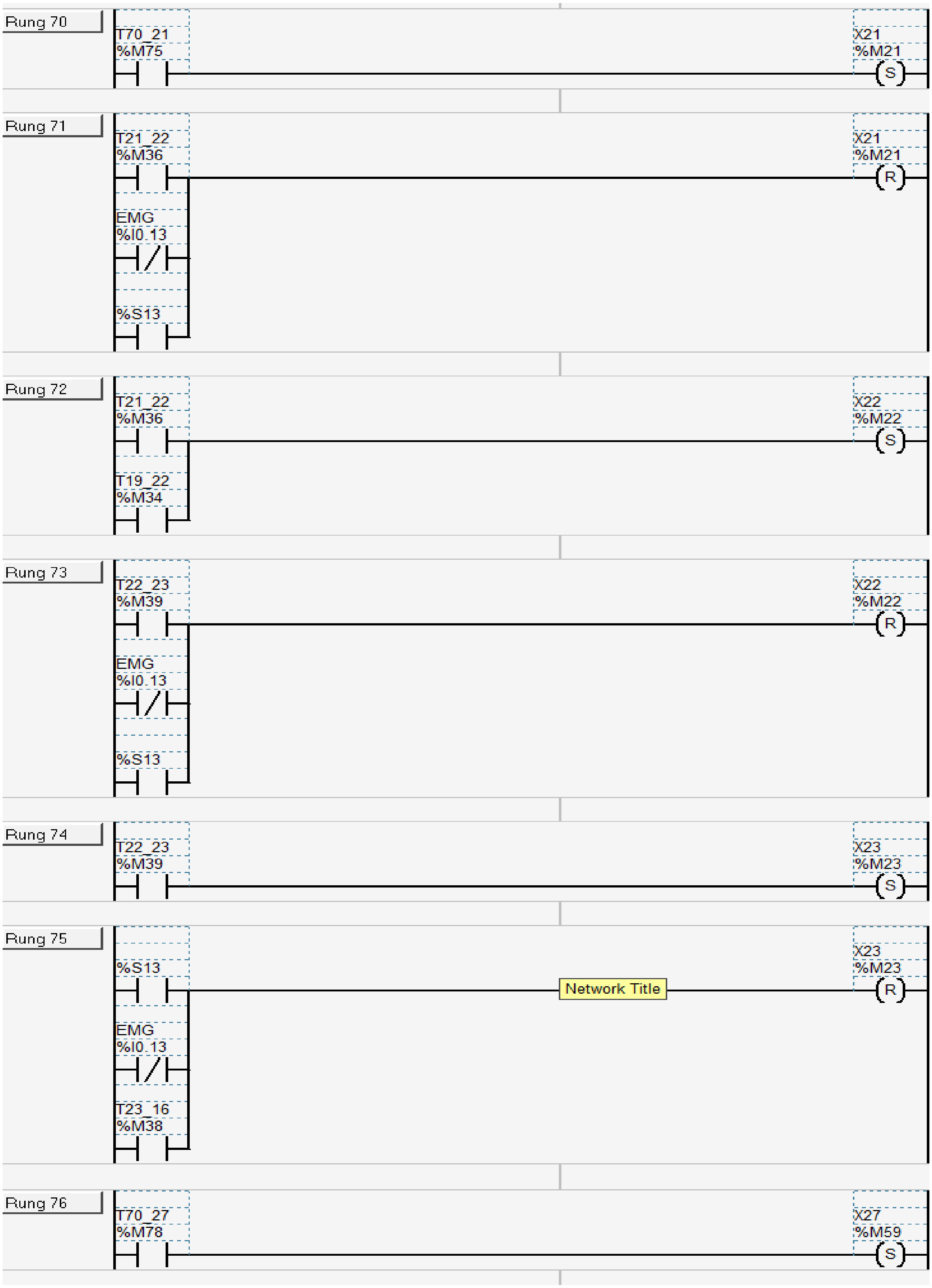
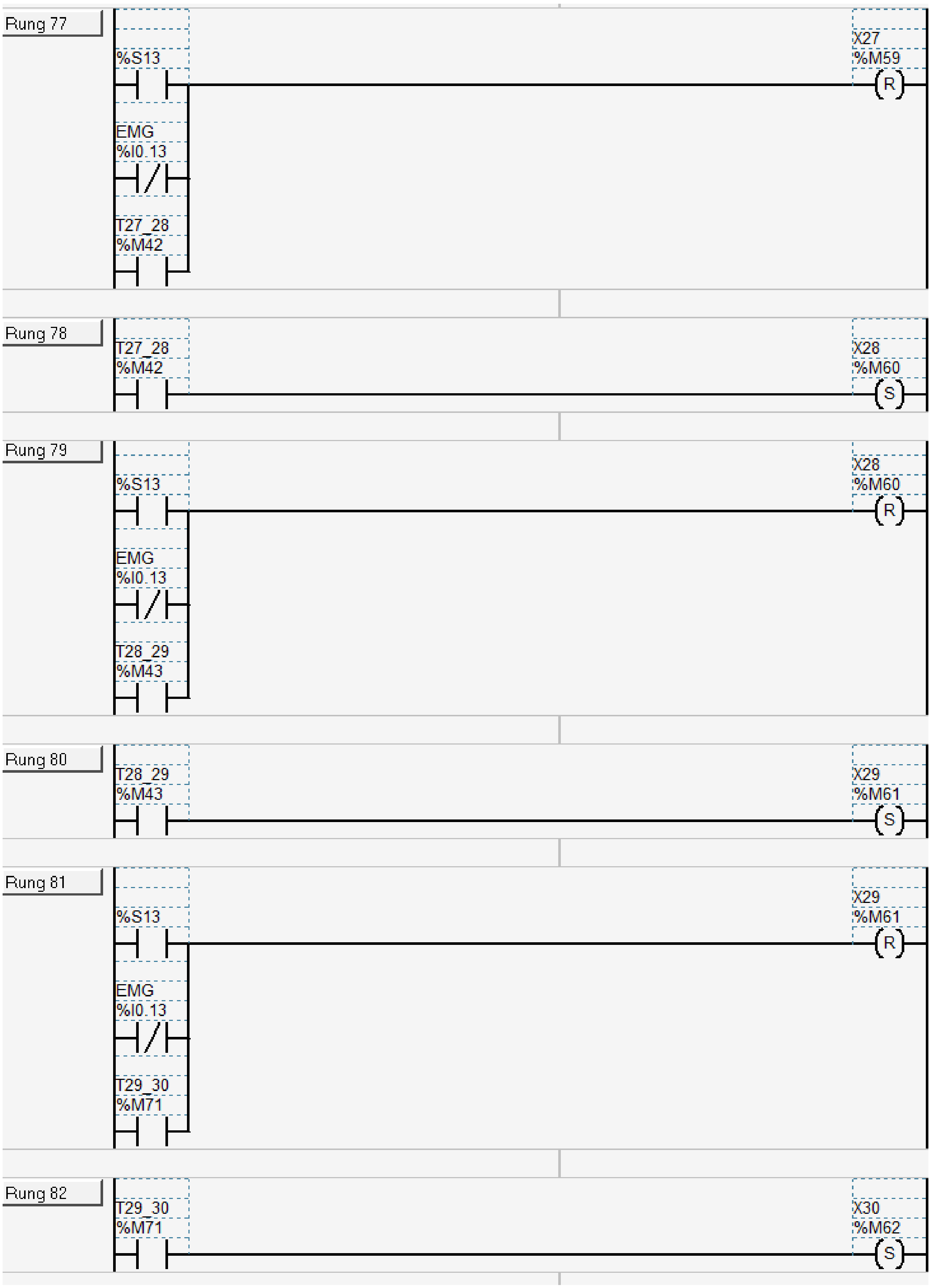
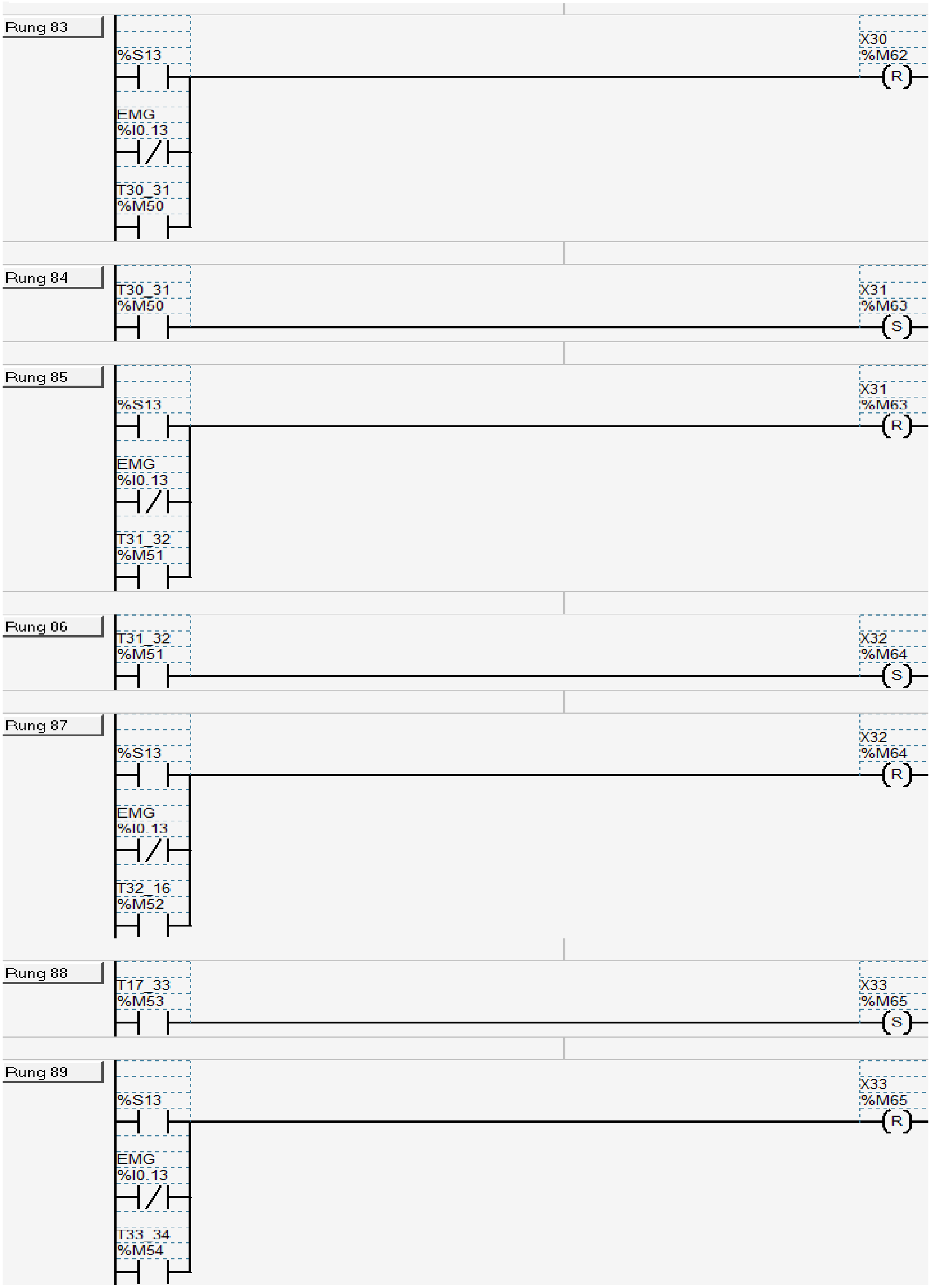
X14
%M16
S
Rung 60
T13_15
%M49
X15
%M15
S
Rung 61
T26_16
%M30
EMG
%I0.13
%S13
X14
%M16
R
X15
%M15
R
Rung 62
T26_16
%M30
T23_16
%M38
T32_16
%M52
T35_16
%M56
X16
%M79
S
Rung 63
%S13
EMG
%I0.13
T16_17
%M31
X16
%M79
R


Rung 64
T16_17
%M31
X17
%M17
S
Rung 65
T17_18
%M32
T17_33
%M53
T17_36
%M72
EMG
%I0.13
%S13
X17
%M17
R
Rung 66
T17_18
%M32
X18
%M18
S
Rung 67
%S13
EMG
%I0.13
T18_70
%M76
X18
%M18
R
Rung 68
T70_19
%M37
X19
%M19
S
Rung 69
T19_22
%M34
EMG
%I0.13
%S13
X19
%M19
R


Rung 70
T70_21
%M75
X21
%M21
S
Rung 71
T21_22
%M36
EMG
%I0.13
%S13
X21
%M21
R
Rung 72
T21_22
%M36
T19_22
%M34
X22
%M22
S
Rung 73
T22_23
%M39
EMG
%I0.13
%S13
X22
%M22
R
Rung 74
T22_23
%M39
X23
%M23
S
Rung 75
%S13
EMG
%I0.13
T23_16
%M38
Network Title
X23
%M23
R
Rung 76
T70_27
%M78
X27
%M59
S


Rung 77
%S13
EMG
%I0.13
T27_28
%M42
X27
%M59
R
Rung 78
T27_28
%M42
X28
%M60
S
Rung 79
%S13
EMG
%I0.13
T28_29
%M43
X28
%M60
R
Rung 80
T28_29
%M43
X29
%M61
S
Rung 81
%S13
EMG
%I0.13
T29_30
%M71
X29
%M61
R
Rung 82
T29_30
%M71
X30
%M62
S


Rung 83
%S13
EMG
%I0.13
T30_31
%M50
X30
%M62
R
Rung 84
T30_31
%M50
X31
%M63
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Rung 85
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EMG
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X31
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R
Rung 86
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X32
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S
Rung 87
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EMG
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X32
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R
Rung 88
T17_33
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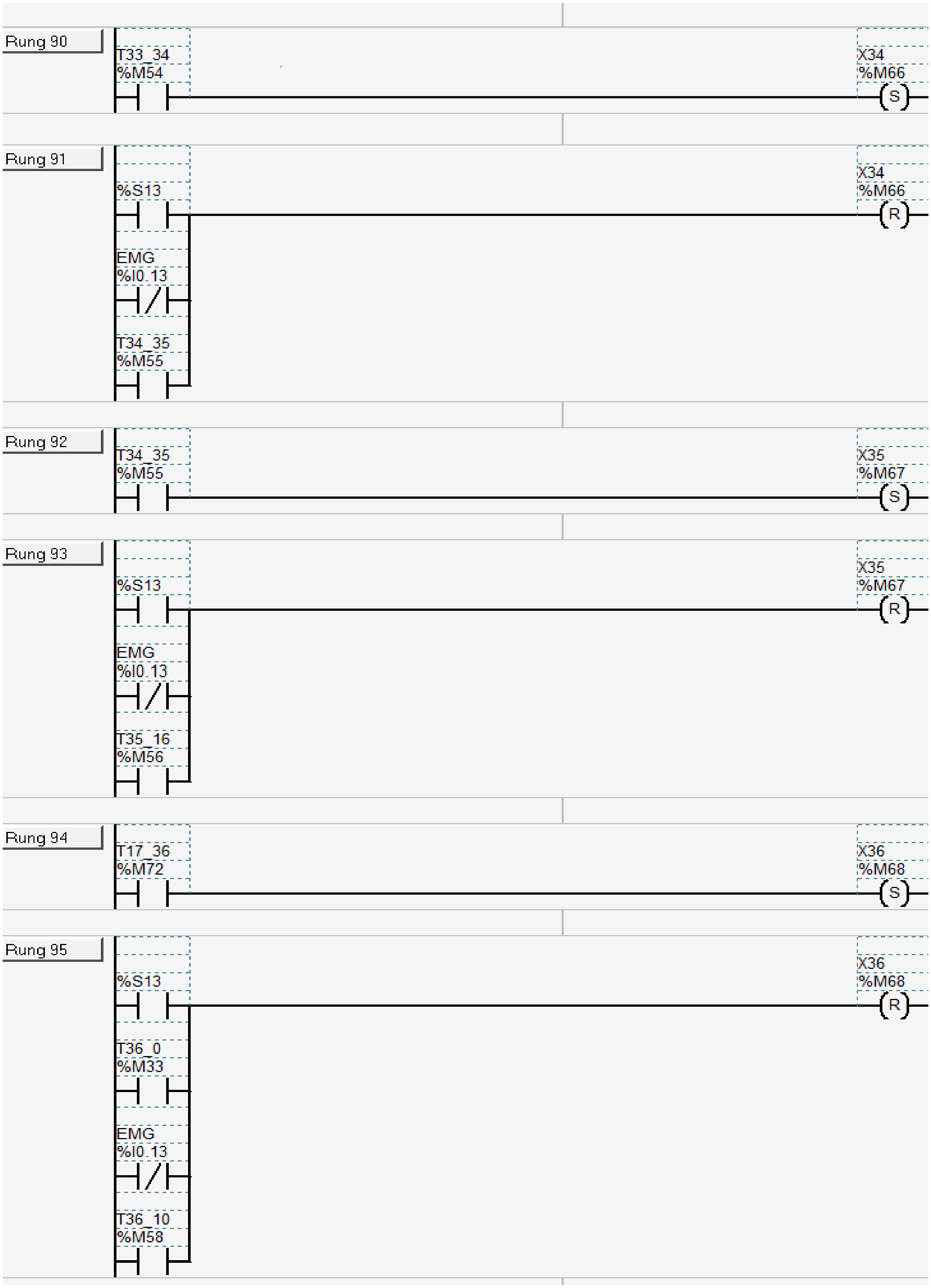
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R
Rung 92
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S
Rung 93
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X35
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R
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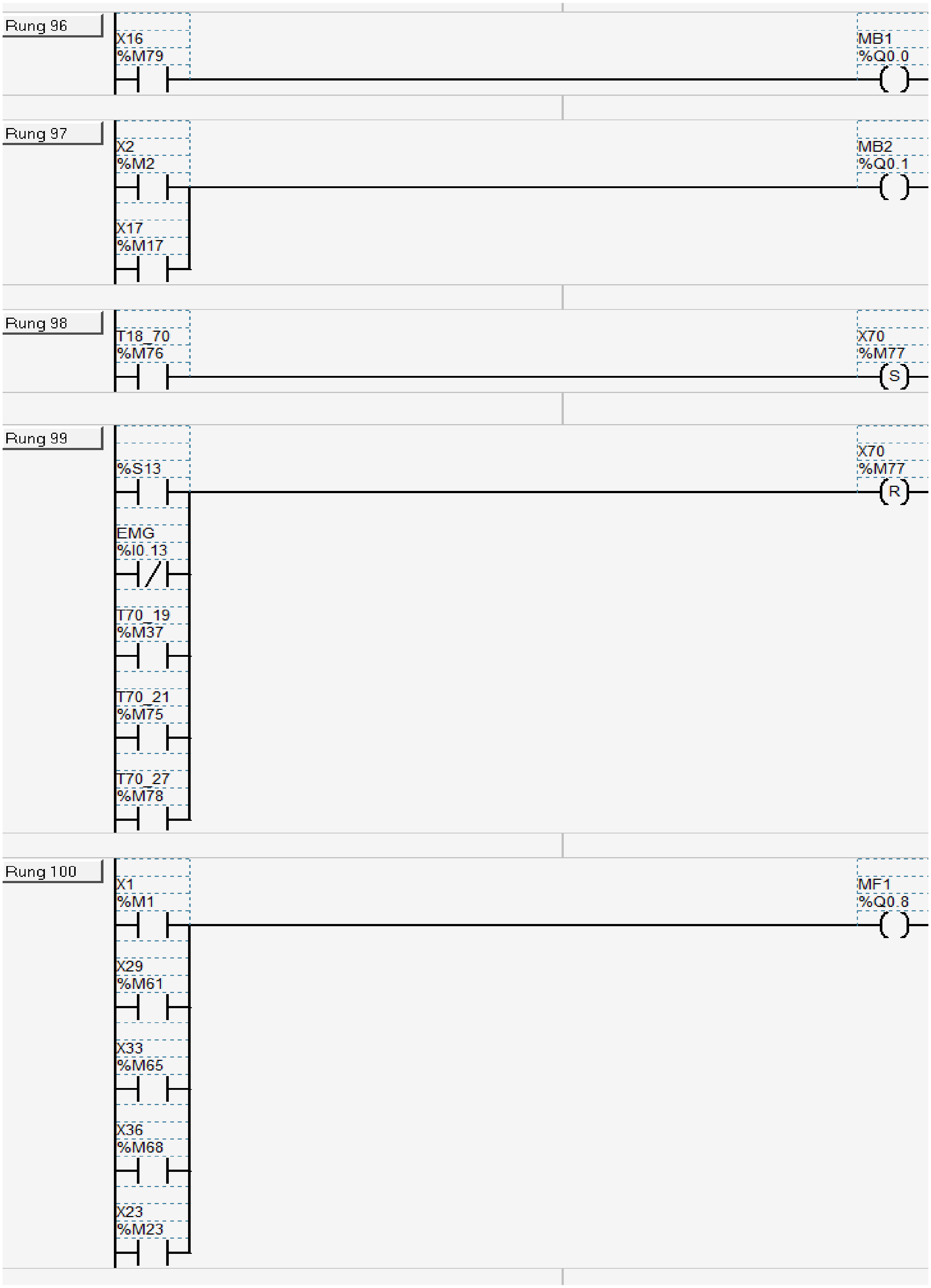
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T18_70
%M76
X70
%M77
S
Rung 99
%S13
EMG
%I0.13
T70_19
%M37
T70_21
%M75
T70_27
%M78
X70
%M77
R
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MF1
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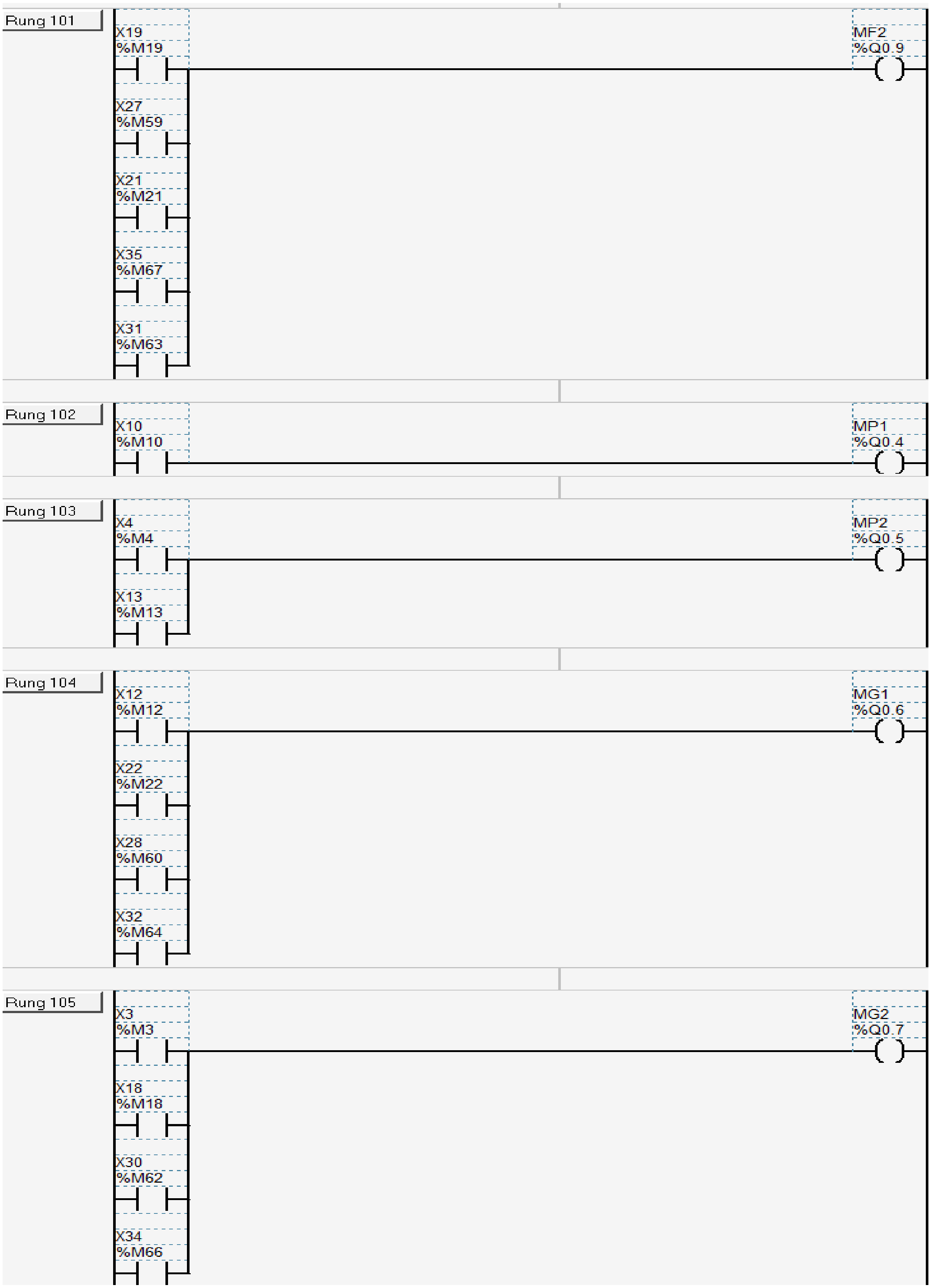
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X10
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MP1
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Rung 103
X4
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X13
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MP2
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X12
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X22
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X28
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X32
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MG1
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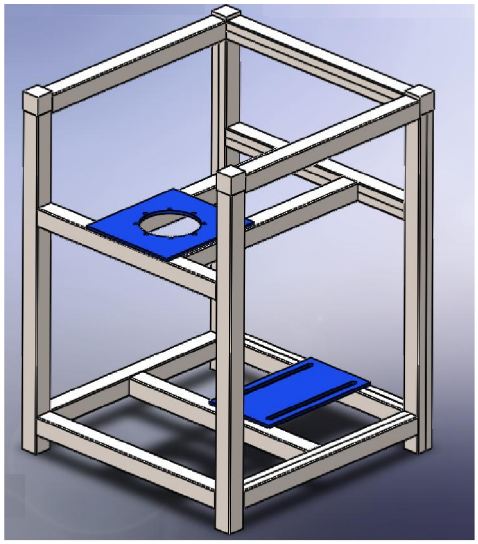
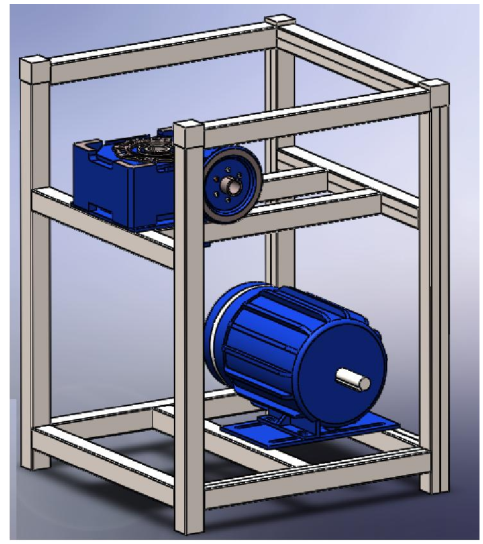
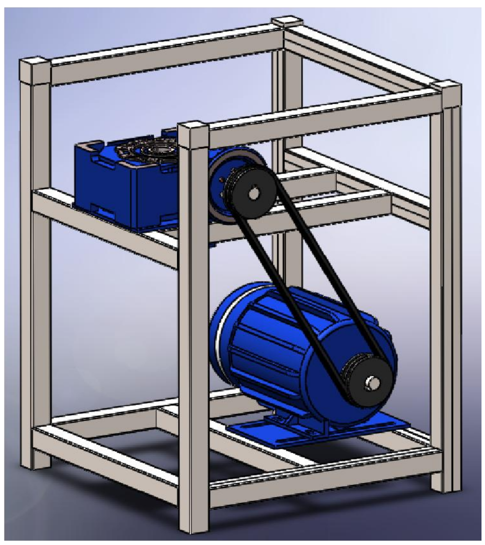
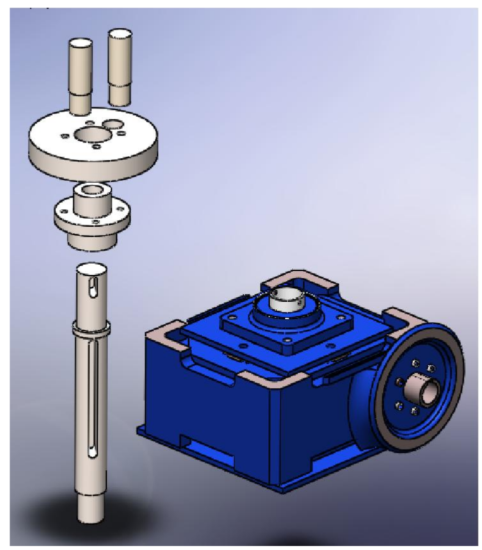
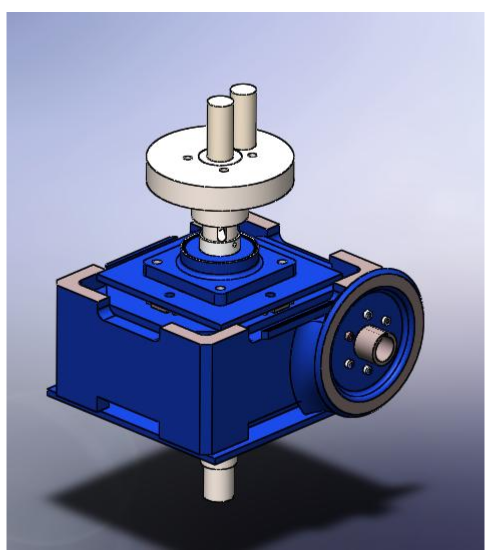
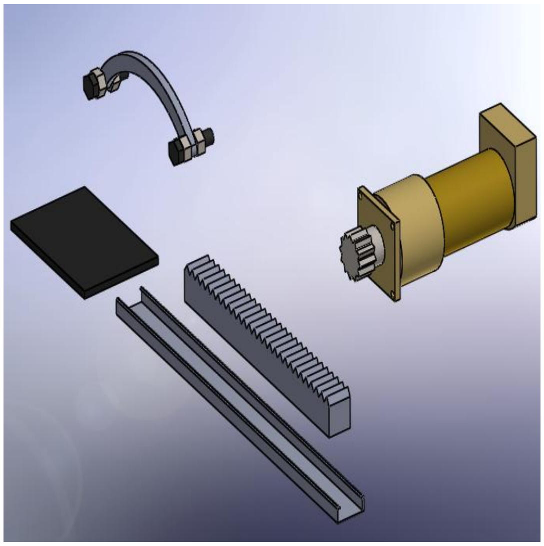
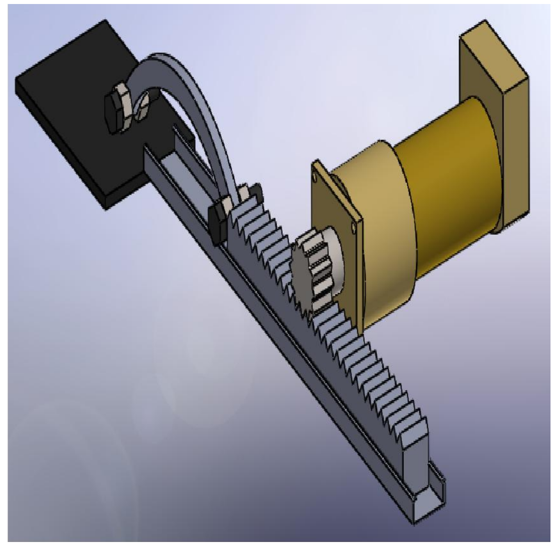
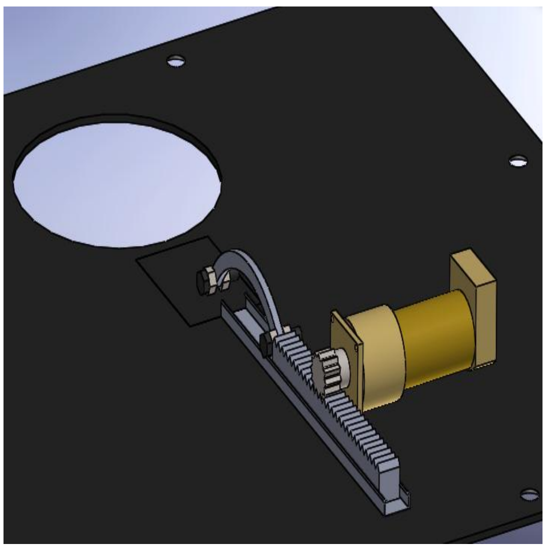
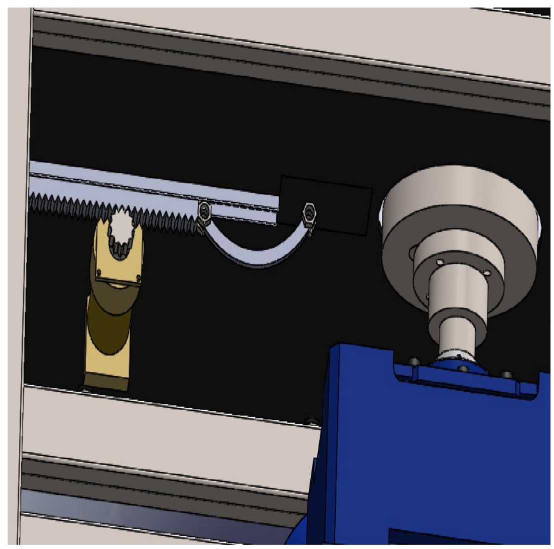
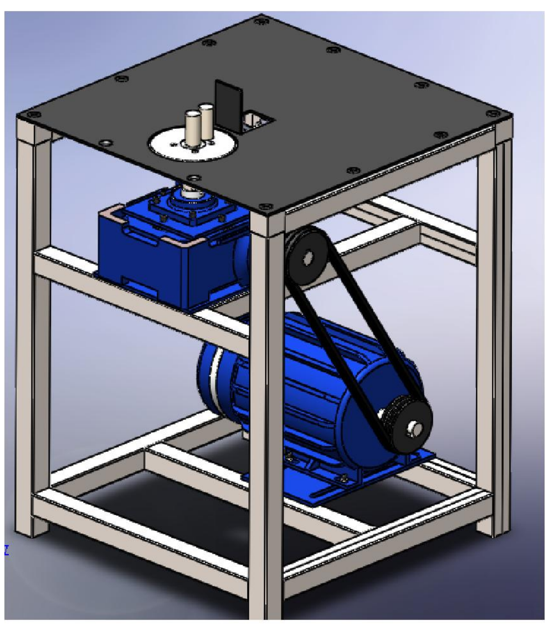
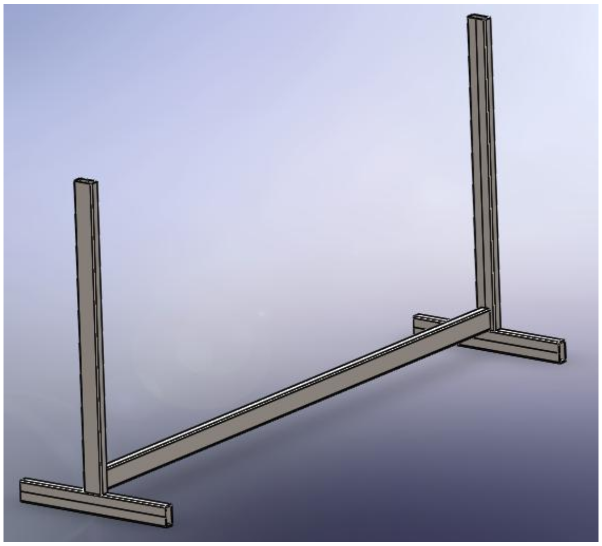
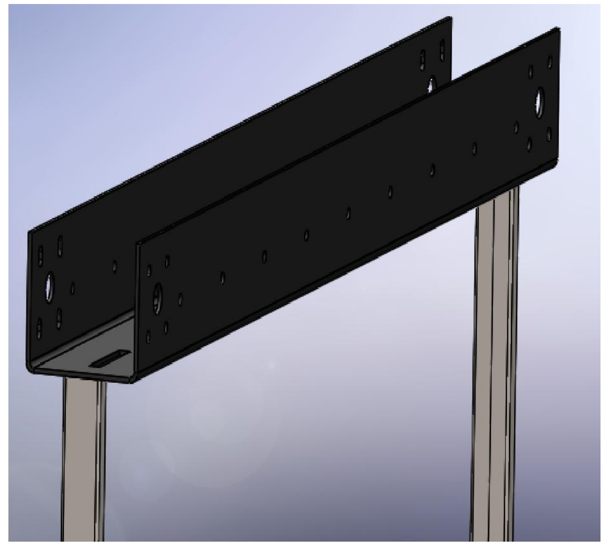
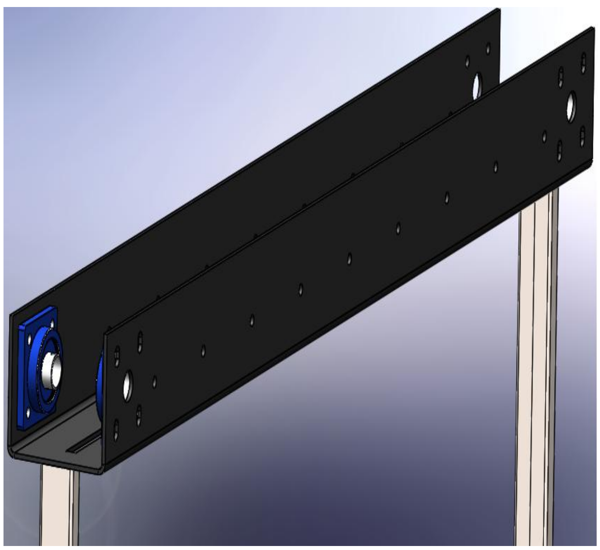
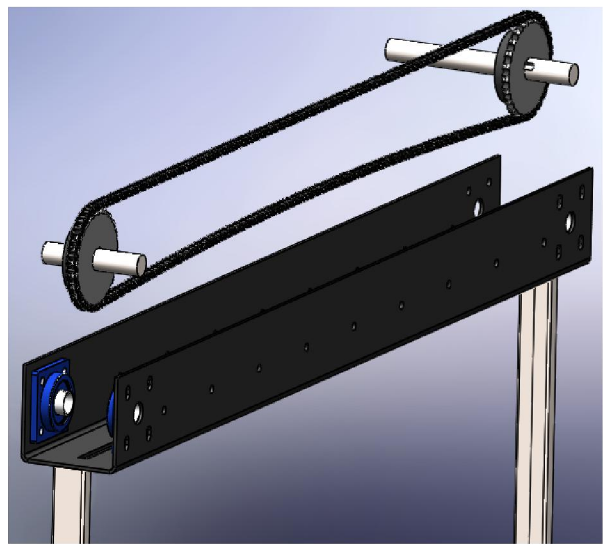
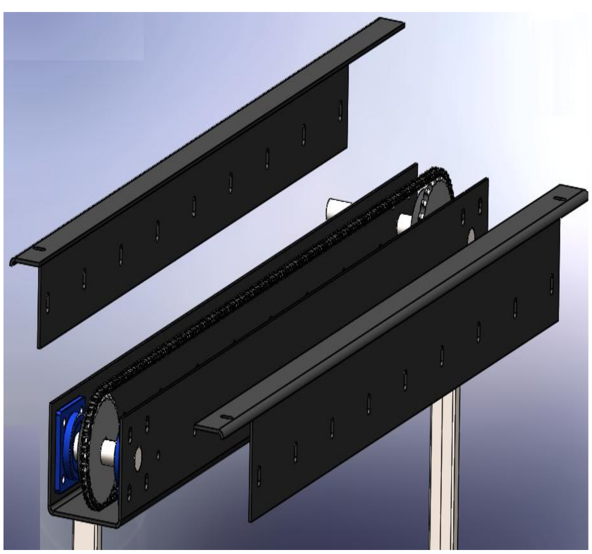
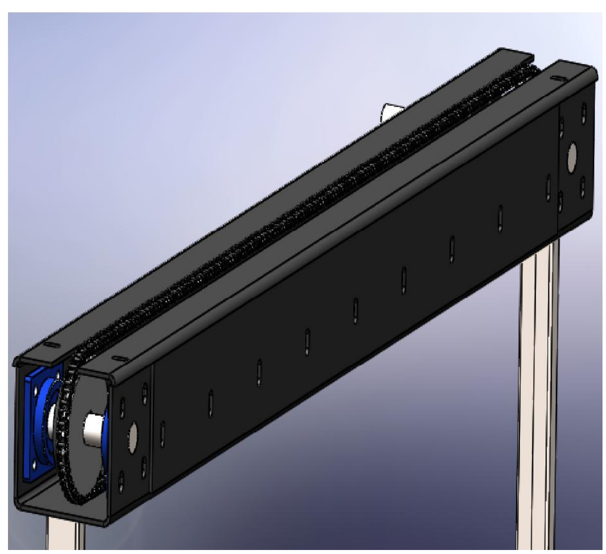
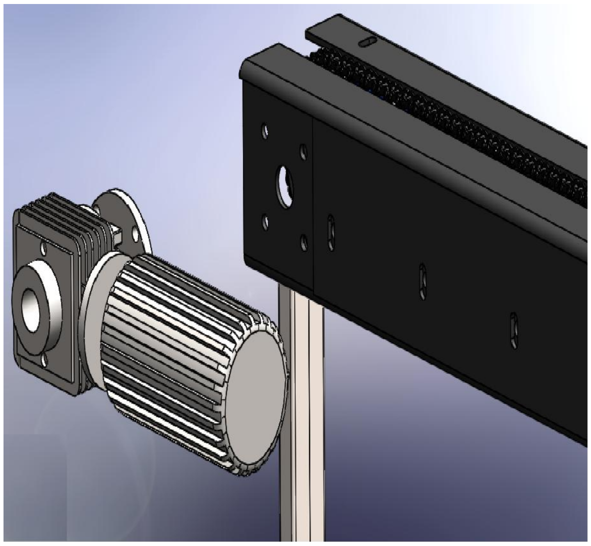
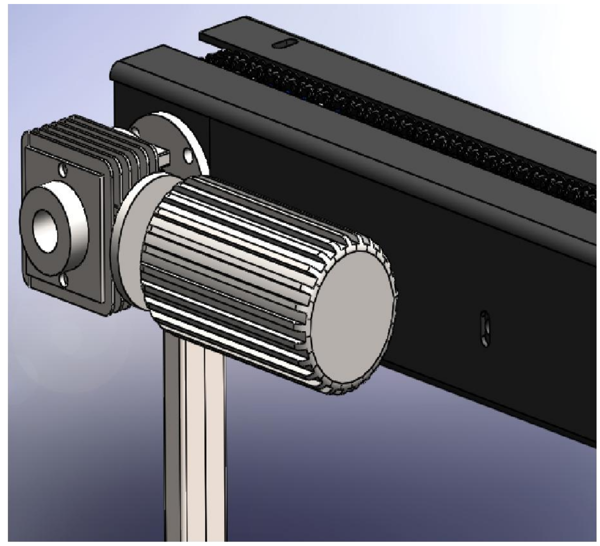
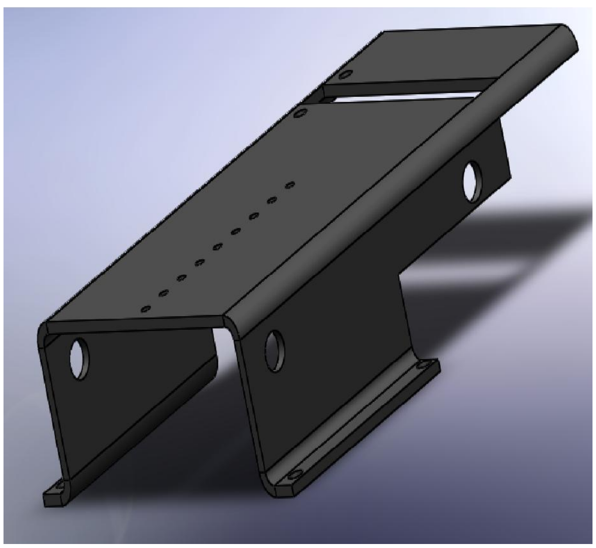
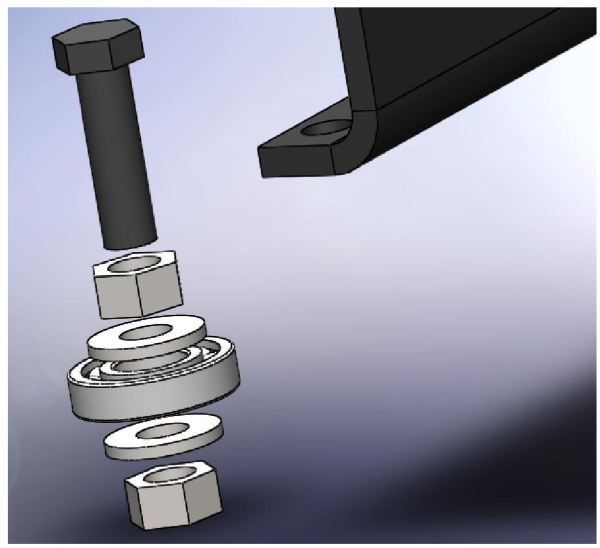
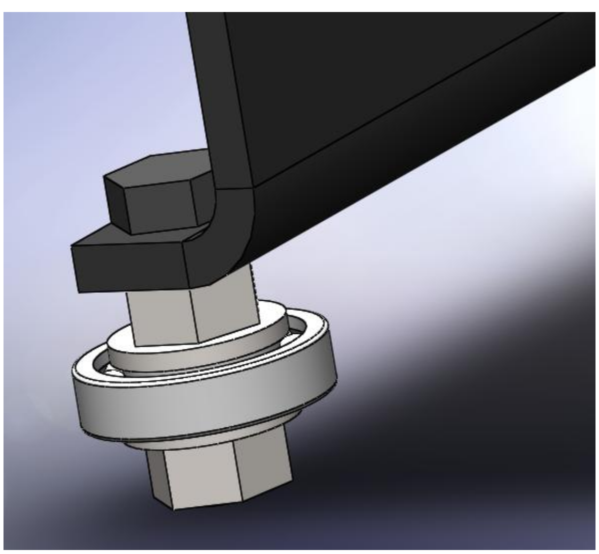
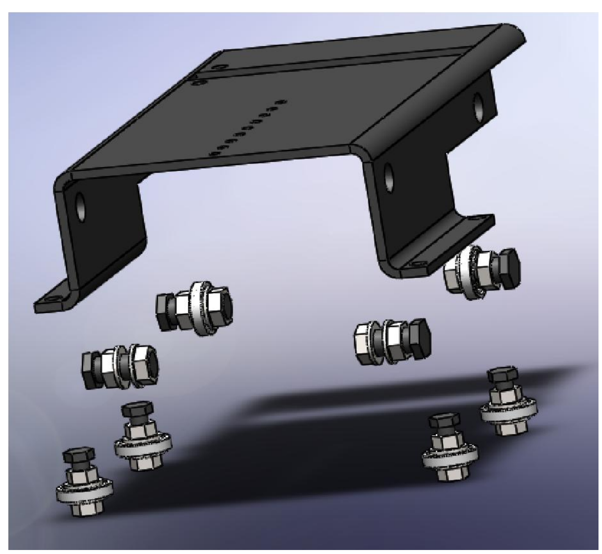
Appendix B

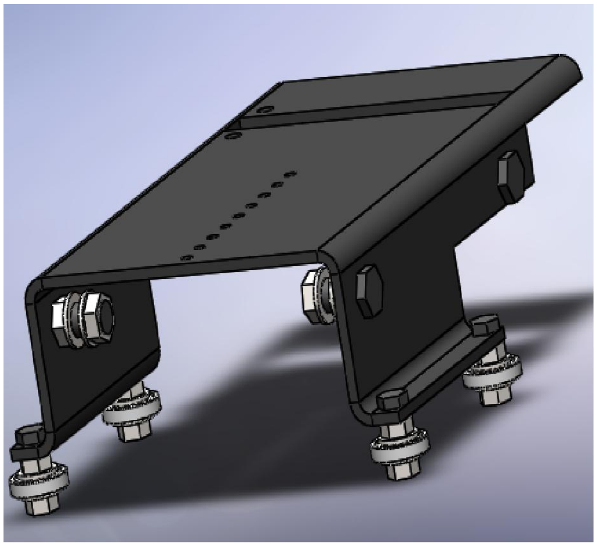
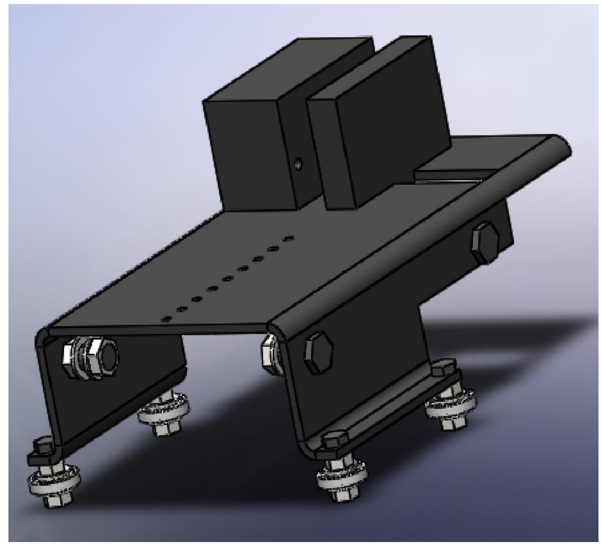
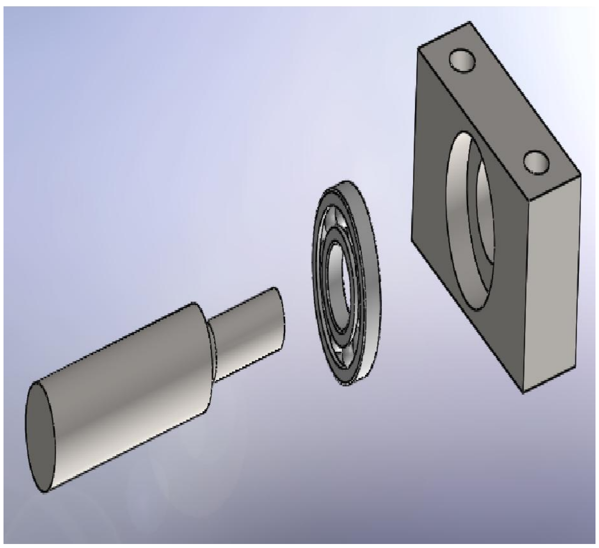
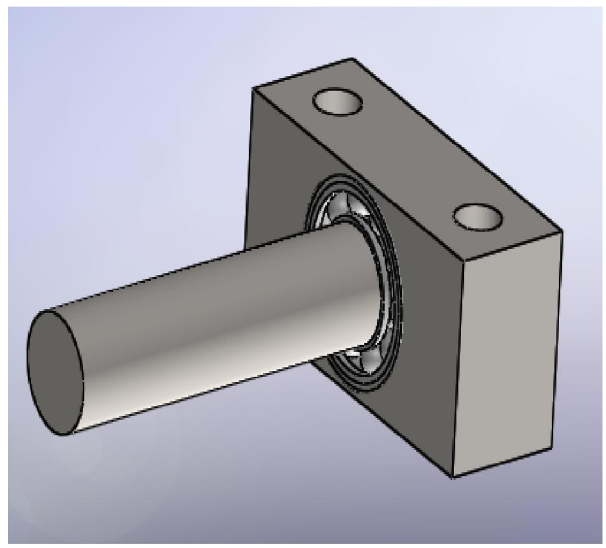
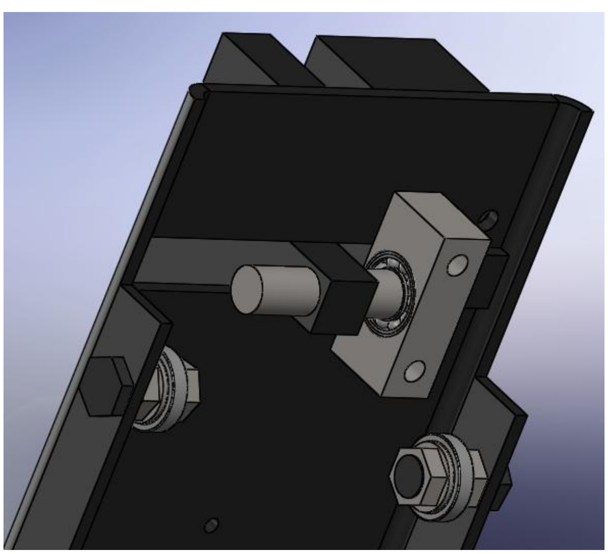
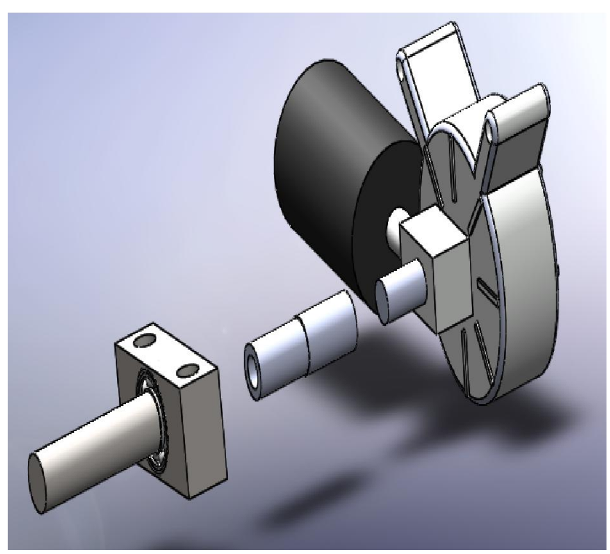
Machine assembly

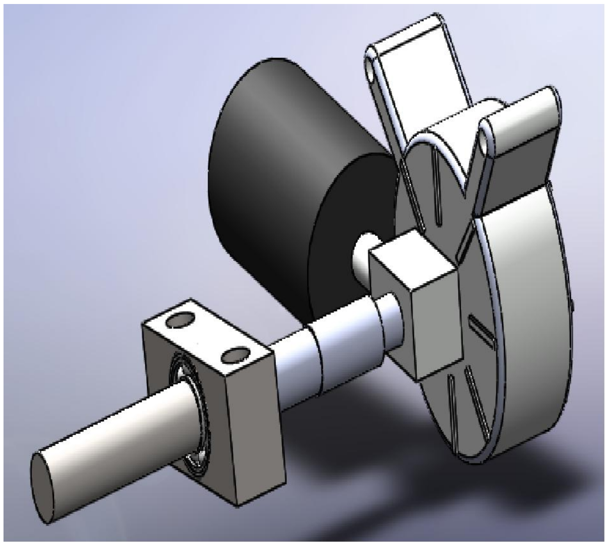






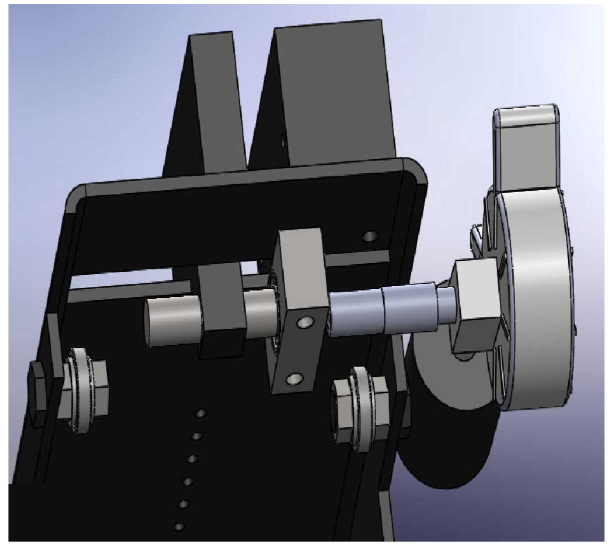






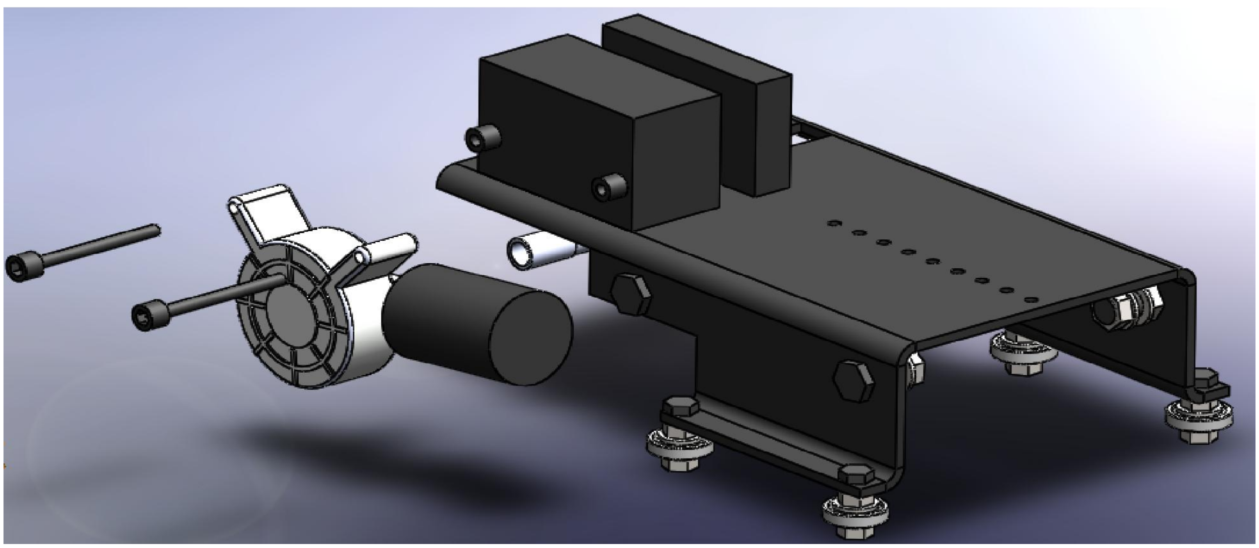







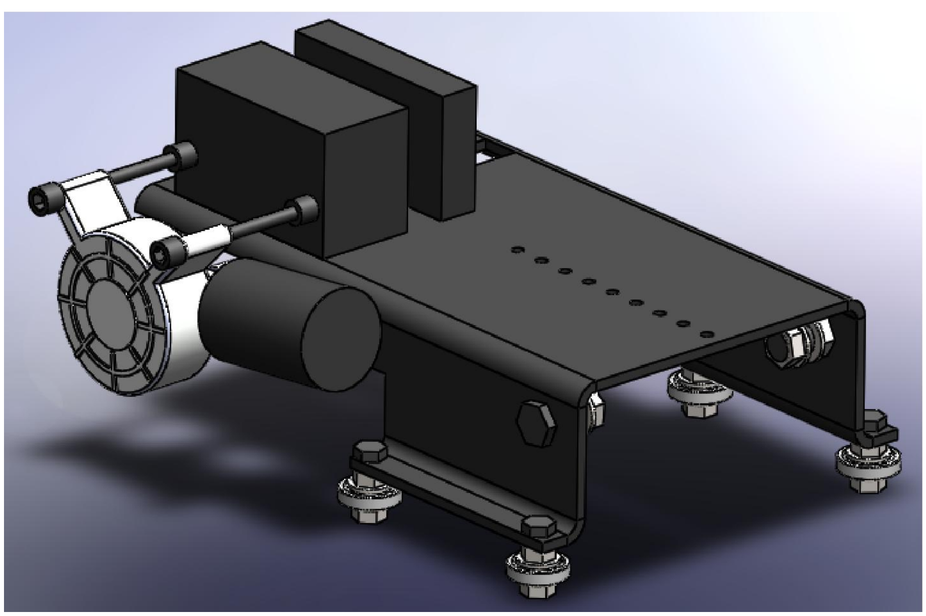







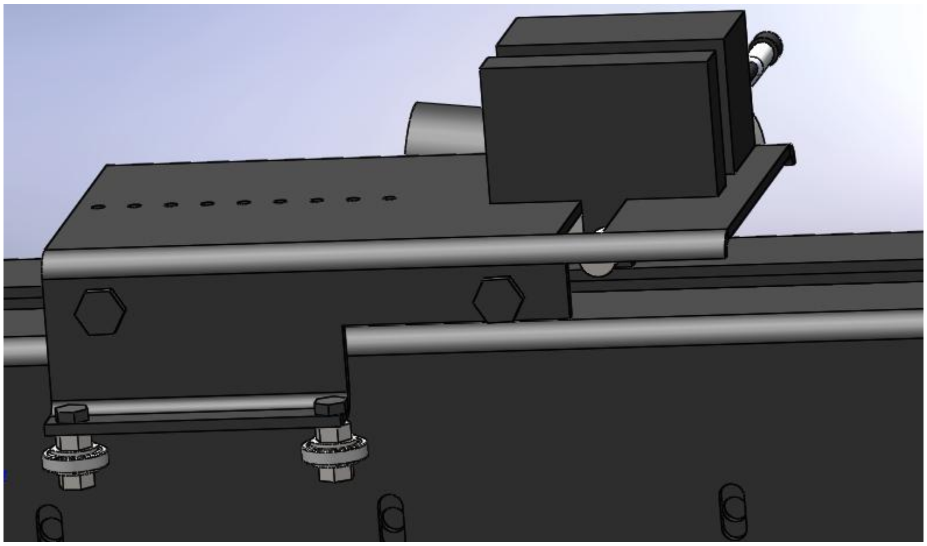







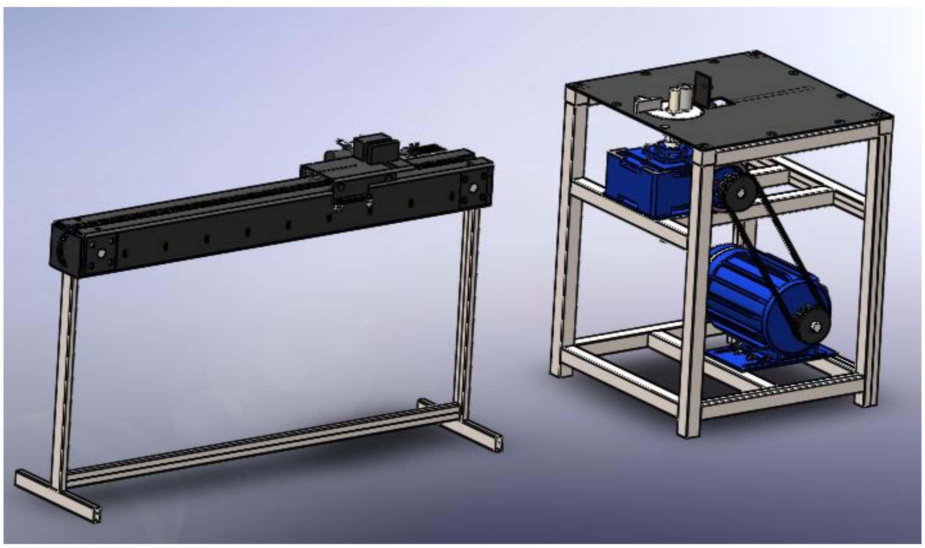


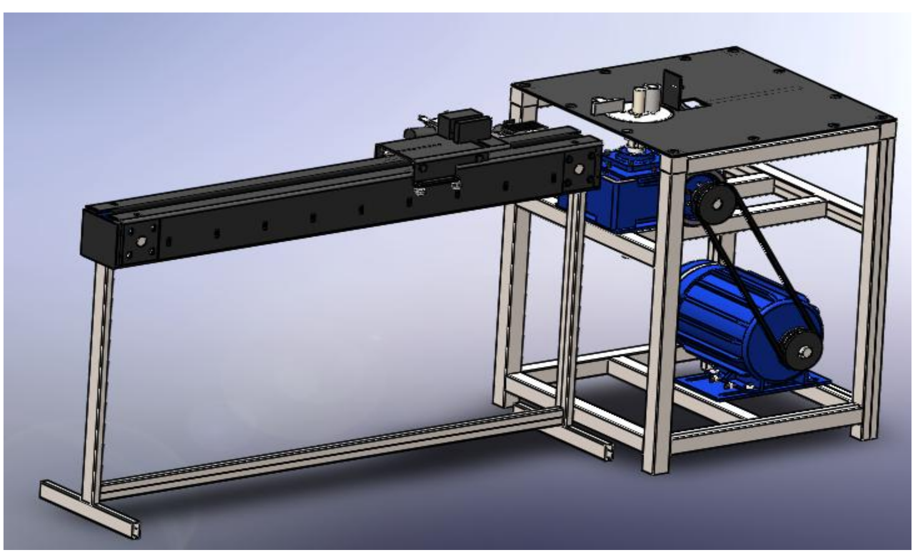


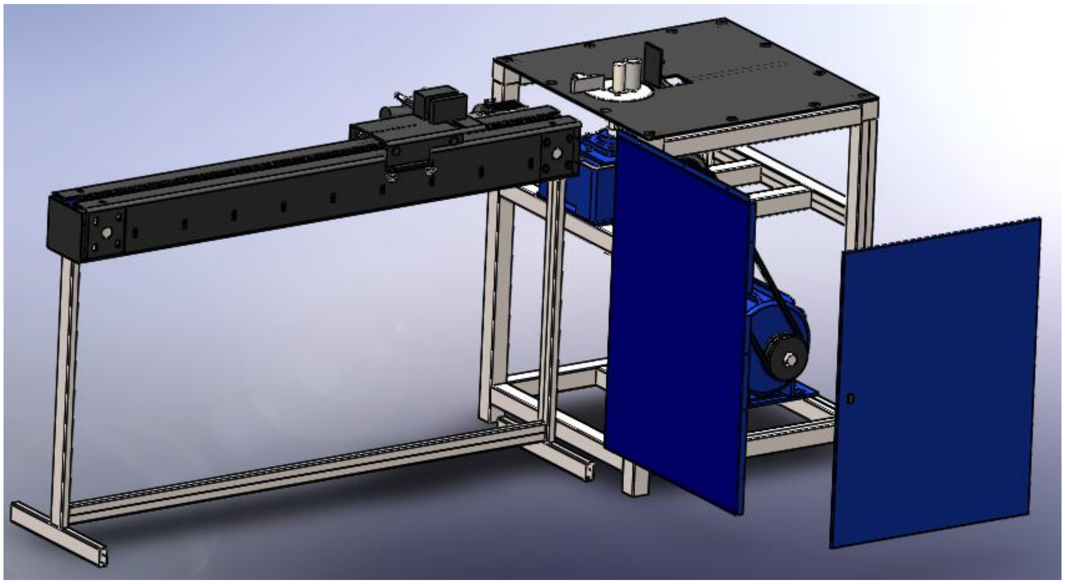


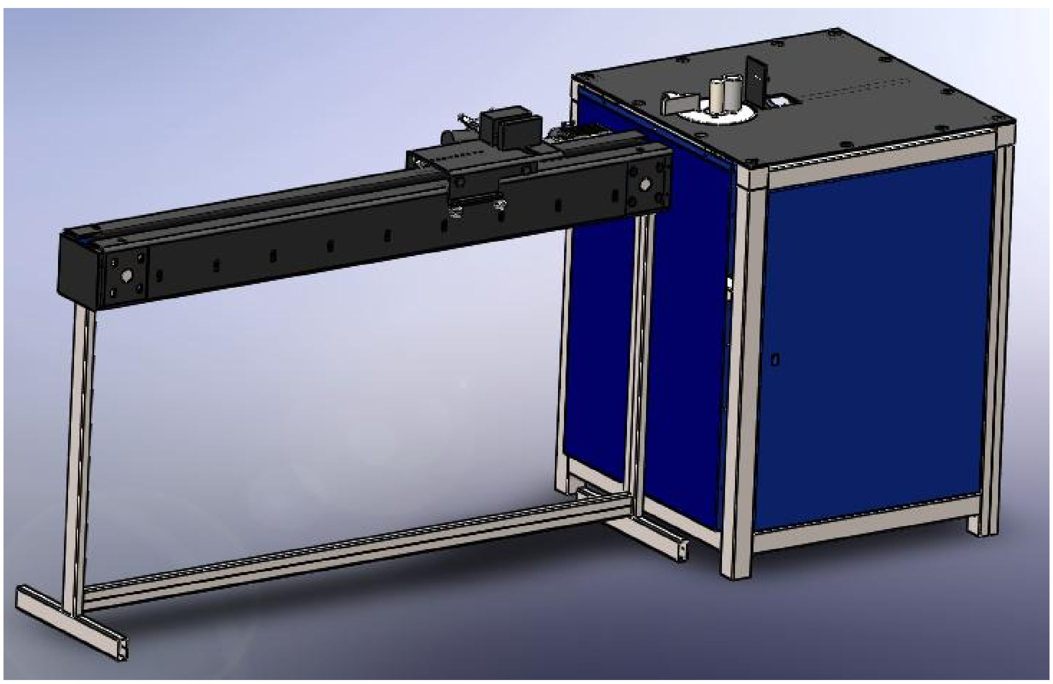












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