TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
DEPARTMENT OF ELECTRICAL POWER ENGINEERING AND MECHATRONICS

STUDY ABOUT AUTOMATING THE HAMMERING PROCESS OF FORM COIL INSERTION INTO GENERATOR STATORS

KUJU-MÄHISE GENERAATORI STAATORISSE AUTOMATISEERITUD SISESTUSTEHNOLOOGIA VÄLJATÖÖTAMINE

MASTER THESIS

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Tallinn 2021

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Department of Electrical Power Engineering and Mechatronics

THESIS TASK

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Study programme: MAHM02/18 – MSc. Mechatronics

main speciality:

Supervisor(s): Leo Teder – Assistant Teacher TalTech , Estonia

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Thesis topic:

(in English) Study about automating the hammering process of form coil insertion into generator stators
(in Estonian) Kuju-mähise generaatori staatorisse automatiseeritud sisestustehnoloogia väljatöötamine

Thesis main objectives:

1. To study about the possibility of developing a system for automating the hammering process during coil insertion
3. Placing the coils manually to the stators and using a device for pressing the coils to the slots
4. Reduce the human efforts and so as to reduce human injuries

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Studying the factory workflow and complete winding process	10/02/2020
2.	Finishing different possible design developments and simulation of the device in software	25/03/2021
3.	Finishing different possible design developments and simulation of the device in software	30/10/2020
4.	Result analysis and finishing the research	10/04/2021

Language: English **Deadline for submission of thesis:** 18 May 2021

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PREFACE

The research work has been carried out at the ABB M&G factory environment Juri, Estonia under the principle supervision of assistant teacher Leo Teder. This research work investigates the possibility of developing an automated device for coil insertion process in generator stators. The study has carried out based on the factory workflow regarding coil insertion process.

I like to take a moment to thank and appreciate my industry supervisor from ABB factory Erko Lepa. My supervisors shared the necessary ideas and corrected me throughout my entire research to achieve my goal. I benefited from discussing my ideas with teaching supervisor and company. I wish to express my sincere gratitude to Laas Mahl who was production engineer lead at M&G factory, suggested the research topic to the author. It was his idea and motivation to start doing research study on this. Kaarel Lassel, engineering manager from ABB M&G factory who has guided me and helped me during my industrial visit to ABB plant where I got the exposure and learned about the daily workflow regarding generator assembling and manufacturing. This research was difficult even though the scholar has developed the design which has a major impact on future works.

This paper is ultimately focused on daily work analysis of coil insertion into generator stator slots. By doing this study, author has developed and learned new knowledge and tools in robotic tool development which can decrease human difficulty in process and further increase in efficiency. I’m showing my sincere thanks to Professor Mart Tamre and Even Sekhri for giving guidelines and motivation on thesis writing.

Dhananjayan Choondapurakkal Dharmarajan

List of abbreviations and symbols

% - Percentage

2D - 2 dimensional

3D - 3 dimensional

DOF - Degrees of freedom

F - Force

FEA analysis - Finite element analysis

FSCW - Fractional slot concentrated winding

HDPE plastic - High density polyethylene

IPF – Industry protection factor

IRB - Industrial robot

KG – Kilogram

L - Length

M&G - Motors and generators

MM - Milli meters

mm/s - Milli meter per second, displacement unit

N - Newton

N/m2 - Newton per milli meter square, force unit

PMs - Permanent magnets

RPM - Revolutions per minute

SPSGs - Salient-pole synchronous generators

T – Thickness

W – width

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1. INTRODUCTION

The goal of this research work is to design and develop a system for automating the hammering process for coil insertion during the winding development in generators in ABB M&G Factory. Meantime the workers are inserting the coils into the generator main core by manually. Clearly, they are using a rubber or plastic hammer for hammering with the help of a flat ruler like material (with a thickness ranging from 1 centimetre to 2 centimetres depending upon the size of the generator core) which helps the workers to insert them. The main principle over here is, they have to make winding from bottom to top of the winding cavity or filling area.

The existing solution is already utilized, so called manual hammering process. As mentioned before, includes workers comfortable working zone and the possibilities for occurring errors which effects the quality of the whole product. The main issue with the workers facing is all about this filling area or cavity. More clearly, if it is a larger diameter generator core then they can do hammering more comfortably. But if it is a small diameter generator core, it is not an easy task for them. Also, when doing hammering process, it may affect the coil insulation, coil quality, and its reliability which result in so called human errors. For the problem solving, the researcher should know about the working cycle and processes of course. Then, should have to collect and analyse the data which include measurement of the working table, mechanisms evolved in these processes, generator size, coil data which include thickness, length, level of winding and so on. Then need to make a deep study about all these data. Developing the sample model of existing working table in design software. Developing the necessary calculations for pressure, force distribution, length of movement, degrees of freedom and all other calculations for the developing device. Then development of the sample model of the expected device. Checking and inspection by terms of theoretical approaches.

Development of a coil insertion device should be capable to solve all of these issues including human errors. The motivation behind is, finding a technical solution for this subject from Engineering principles. ABB M&G factory assembling workers are the beneficiary part with this development. Development of this research topic could solve the workers problems and could improve the production efficiency with good command of workers job quality. This research includes the approaching for finding the solutions for developing the device which mainly include calculations, measurements, and device design.

The demand for automated winding technology has been raised as a durable and efficient stator winding method for electric machines. Automated stator winding technology is widely used, for small and medium sized electric machines with high production volumes. New research works are going on to develop new automated stator winding methods providing higher product efficiency, performance, facilitated assembly and increased assembly flexibility. However, not every manufacturing industries and companies are not following the common winding technology as they are aiming to develop their own technology for cable winding.

1.1 Research study

This research is studying primarily on designing and analysis of an automated arm, which diminishes the human effort and might have a great impact on production rate. This alter can propel the industry and scholastics such that the trade of the firm is expanded. The study aims to reveal the possibilities of automating the coil insertion process in generator stators. The coil insertion process is very labour intensive and very complicated to automated. There are lot of challenges the researcher has to study about. There are smaller to larger sizes of generator stators available and manufactured in the industry. The research is carried out in every aspect of the industry and coil insertion process including smaller to larger sizes of stators.

1.2 Research statement

The thesis examines the possibility and reliability of an automated device or tool development for hammering process for form coil insertion in generators. The main goal of the study is to design automated device for hammering process. It means placing the coil manually to the stator and insertion by using a device.

1.3 Research objective

Designing, modelling and simulation of the insertion device is the main objective of this research. The process includes primarily of observing and studying of the present manual work process at factory. It means that the research should be carried out through the study of factory tasks and the factors that affect and make impact during the development of the supposed automated device.

- To study about the possibility of developing a system for automating the hammering process for coil insertion on generator stators

- Placing the coils manually to the stators and using a device for pressing the coils to the slots
- Reduce the damage caused by the hammering process
- Reduce the chances of the human injuries that could happen during mis handling of hammering.
- Theoretical approach of simulation and analysis
- Analysing the size of the coils, weight and thickness which are necessary during design of the tool
- Slots width and related dimensions
- Data collection of the different generator stator

The result is the successive simulation of proposed insertion device.

1.4 Research questions

- How to implement the automatic coil insertion process in stator winding process?
- The possible outcomes and challenges arising during the design development.
- How extend this research work would be useful
- Who or how would this research work be beneficial for

2 LITERATURE REVIEW

The research of generator stator winding automation is the primary research focus of this industry. It complicates the tasks of researcher and needs to start each research phase. Related to motor cable winding process, the researchers from Uppsala University developed three cable feed tool prototypes, which were evaluated experimentally and validated for the required applications. Important performance parameters were proposed and discussed, including suggestions for further development. However, they have completed the process of developing robust, compact and powerful tools with fully integrated controls in industrial robot controls [2]. The experimental results presented in this article are very satisfying for the referenced article work. Therefore, the updated cable entry design is another important step towards the industrial solution of stator cable robot winding. However, it resulted and stating that the design of the tool is somewhat limited. The advanced concept of cable feeding can also be used in similar applications to a certain extent, such as cable laying, cable production, and clamping or feeding other components with high precision and precision [2]. Another study showed the use of concentrated fractional slot windings (FSCW) in large-scale salient pole synchronous generators (SPSG). Determine the development of generators using optional permanent magnets (PM). Compared to other rotors in this category, all-pole rotors have a larger diameter and a shorter length. They are usually used in motors with low speeds such as 100 to 1500 rpm. Compared with traditional synchronous generators, centralized slot winding technology can obtain a lighter, cheaper and more efficient generator through a simpler design [2].

It is very important to review and analyse acquisition techniques. They are mainly divided into actuated grip, grip with controlled stiffness and grip with controlled grip. By using an elastic structure that is moved by an external electromagnetic motor and passively adapts to the shape of the object, flexible grip can be achieved. The main feature of the acquisition trigger method is that it does not acquire any active elements that come into contact within the structure, which can obtain high mechanical strength. A common method of gripping with controlled stiffness is to move the clamp frame to its soft structure, expand and wrap the approaching object to pick it up, and finally squeeze the frame to secure it to the cage. Types of adhesive grip, such as tendon deformation and contact deformation [10]. This method can produce higher clamping force without increasing the clamping budget. In addition, the structure of the gripping strategy can be expanded by local hardening, so that the shape can be changed. The freedom of every move. Adhesion is the attraction between two surfaces. This results in a shear stress proportional to the normal pressure generated. The soft gripper with built-in gripper can generate higher clamping force due to its higher shear friction [5][8][10]. At the same time, the clamping force perpendicular to the surface of the object is much smaller than the clamping force when holding the trigger, which makes it possible to handle very fragile objects. This literature review helped maintain this scientist An overview of other technologies, such as capillary adhesion methods [5] [7] [8] [10] [21].

Grippers based on the vacuum principle follow the bonding method to grasp objects. Suction cups made of suitable materials use this mechanism and are widely used in industry [9] [22]. They are well explained in Article [10]. Suction cups can be used to actively or passively generate vacuum. Suction cups and objects must be guaranteed. Capillary adhesion is specially used for processing microscopic objects. The grippers using this technique are designed to take advantage of the capillary buoyancy of the water and overlap the handle with the object [10]. The contact angle can be controlled by applying a low-voltage electric field on the liquid bridge, thereby changing the contact angle. This means that the surface tension has changed [10]. These types of tweezers work well in micromanipulation because they dominate capillary forces in the micrometre to nanometre range. Since capillary clamps hold objects together through liquids, they help reduce the risk of possible damage. However, the reduction properties of materials with different surface energies are still unclear [10] [21] [22].

The authors from [10] [15] [16] reveals the importance and development factors of soft pliers. This work shows that the soft manipulator can be mainly used in the food and agricultural industries. In addition, the author examined the different types of materials and characteristics used to develop soft tweezers. Important research results in [23] point to electro-adhesive technology and pneumatic clamps. This article highlights the main findings. A common method of gripping with controlled stiffness is to move the pliers structure to approximate and wrap it into its soft structure. The purpose of this method is to take this into account and finally tighten the structure to secure it to the cage. The review of the literature also helped to become familiar with various viscous terms, such as spreading and contact deformation [10]. Clamping force minimize the fixed budget. In addition, local hardening can extend the structure of the gripping strategy, allowing the freedom to change the shape with one movement. Adhesion is the attraction between two surfaces. This results in a shear stress proportional to the normal pressure generated. A soft gripper with an integrated handle can produce a higher clamping force due to its higher shear friction. At the same time, the clamping force is vertical compared to when the trigger is pulled, the surface of the object is much lower, so very fragile objects can be handled. This literature review helps scholar to gain insights into other technologies, such as capillary bonding [5] [7] [8] [10] [21].

The grippers based on the vacuum principle use the adhesion method of the adhered object. Suction cups made of suitable materials use this mechanism and are widely used in industry [9] [22]. This is well explained in Article [10]. Emptiness can be created. Active or passive on the suction cup. Suction can only be performed on a smooth and non-porous surface, so a good seal between the suction cup and the object must be ensured. Capillary adhesion is specifically used to process microscopic objects. This type of technique uses the usually water and is applied to handles and objects [10].

3 SELECTION OF ROBOT MODEL FOR INSERTION

For this research work, it is very important to select the appropriate model and type of the industrial robot. Developing insertion tool should be able to suitable and fitted on the corresponding robotic arm. The researcher has carried out the deep study about the types of robots and models available in the industry. This research work aims to automate the human work of coil insertion into automated device work. Therefore, it is very critical to choose the robot type and mechanism. Below are the given explanation and approaches carried out for the research study.

3.1 Factors considered for the robot selection

3.1.1 Reach of the robot model

It is very important to take in consideration about the reach of the robot and for the work purpose. It is estimated by the links, number of joints and the corresponding dimensions of the robot model. For the coil insertion process, the robot has to start working by moving its arm towards the inside direction. Therefore, maximum level of horizontal reach robot is more suitable for this research purpose. Sample reach calculation by the scholar has been given below,

The length of the generator model selected = 800mm

Inner diameter of the model = 860mm

Outer diameter of the model = 980mm

Length of the tool frame is assumed to be 1100mm

Distance from the robot station to worktable assumed to be 1000mm which is 1 meter. More clearly, this value indicates the distance from the point where robot starts working and to the worktable.

The minimum level of robotic arm reach required for the insertion process is given by,

Minimum level of reach in mm = reach of the robot to the worktable from its station + reach inside the generator stator.

Reach of the robot to the worktable can be calculated by collecting the data of horizontal length of the robotic arm + the displacement possible in millimetres.

For example, for 800mm length core, it is necessary to have robotic arm reach at least 100mm from the entry end. Therefore, minimum reach from is given by

Minimum reach required in mm = 1000 + 100 which is equal to 1100mm.

3.1.2 Speed

Speed of the robot is related with the task and purpose involved in coil insertion process. For the coil insertion process, it is very critical to consider the accuracy and efficiency of the task. If the robotic speed increases, then accuracy decreases. In this process accuracy is much needed to maintain the quality of the coil, insulation and related sensors inside the stator set up.

3.1.3 Payload

Payload means the highest load that a robot is capable to do the work. Here it plays a vital role since the insertion process is related with different sizes of the coils. The robot has to carry the weight of designing tool frame and its related set up.

3.1.4 Repeatability

This is defined as the ability of the robot to return to its position after the task. In this study the robot has to return back after each insertion process. More specifically, after finishing one coil insertion the robot has to return back to its stationary initial position in order to place the next round of coils inside the stator.

3.1.5 Degrees of freedom

This is the level of freedom of the robot motion. This factor indicates the ability of the robot to move forward, backward, upward, downward and toward the left and right directions. For coil insertion process the robot has to be move forward and backward direction mainly. And in some cases, upward and downward directions. Since the coil has left and right-side parts, the robot arm has to be along those direction for the insertion process. Therefore, selection of 6 DOF robot is more suitable for this research study.

3.1.6 Cost of the robot model

cost management is the important part of every research work. It makes more sense when the researcher tries to control the cost and giving more output to the research work.

3.1.7 Protection rating

This value indicates the international rating for the robot model based on its ability withstand against dust particles and water. It is very necessary to find out the IP protection rating for the selected robotic model as it has to work under high protection line. It is good to have a rating of IP67.

3.2 Articulated robots

The purpose of the study about the articulated robots are to find out how extend this type of robots could be used for coil insertion purpose. As the name indicates, it moves along rotary joint coordinates. Since the generator stator frame has a circular shape, the movement of the robot to the inner side of the stator needs to be theoretically carried out. In the very beginning, these types of robots create the challenges of a axes system in order to move and insert the coil. For insertion process, the robot arm must be able to reach inner part which is impossible without an axis. The generator is mounted on a working table which has a size of 120cm X 80cm X 50cm as length X hight X width respectively. It means that axes systems should be adjustable, and it makes the design and study more complex and impossible. As it clears from the below picture (figure 3.1), it is not possible to mounting over the worktable. Assume if the researcher moving with an extra mounting table attached to the worktable, and even though the robot model cannot move inside because it requires path leading to inside which is not possible. Another contradiction to the types of robots are the generation of insertion tool. Since it is moving inside with a robotic arm and it created the less room space inside the stator from smaller to larger diameter of generators.

Figure 3.1 Workstation table at ABB factory. Picture taken from the factory

The worktable is able to adjust and rotate the generator stators with respect to the insertion workflow. Therefore, any external kind of mechanism is not required to move the stator for insertion process. Worktable has a motor which is connected to the rolling parts by a transmitting chain which helps the workers to adjust and rotate the stators.

3.3 Cartesian robots

These types of robots are widely using in industries and contains X, Y, Z cartesian coordinates joints. The failure in the approach towards the articulated robots lead the scholar to study about the possibility of cartesian robots. Since the worktable is very simple and small, the system for movement of the robot arises here as well. But in this case, the researcher succeeded in developing a station for robot. Primarily, the researcher assumed of a workstation for the robot other than working table, where the robot is stationed and doing the insertion process. The cartesian types of robot can be moved inside the stator core by implementing a guide system. In this point the researcher managed to succeed and next step is to find a suitable robot model. After a deep level of research, decided to choose for Yamaha cartesian robots. A short comparison study has given below

Table 3.1 comparison of robots [12][13]

Yamaha MXYx cartesian robot	Yamaha YAR6F robot
Higher level of handling capacity.	Very low level of handling capacity. Only 6 Kg, which is not sufficient enough to operating for larger size of coils.
More range of robotic arm reach which makes capable and work for 1400mm length of generator stators.	Lower level of reach compared to ABB model. This is not sufficient enough to work for larger dimeter stators.
Shortest cycle times which makes increased production capacity.	Cycle times info not available or specified.
Best protection from the industry an maintenance from the manufacturer.	Less info available regarding the robot working environment protection.
Higher level of working area	If the load is more than 1 kg, working area reduces.

From all of the above detailed analysis, the researcher has decided to opt for Yamaha MXYx cartesian robot industrial robot for the research development. The theoretical approach towards this robot model succeeded and next stage is to be developing the insertion device that can adaptable to the robot model. Based on the robot model data in [14], the following conclusions has made.

Table 3.2 Research attributes for the Yamaha MXYx cartesian robot [12]

Number	Attributes	Findings
1	Maximum reach X axis	1250mm
2	Maximum speed on X axis	1200mm/s
3	Maximum reach Y axis	650mm
4	Maximum speed Y axis	600mm/s
5	Degrees of freedom	6
6	Protection rating	IP67
7	Payload	40 Kg
8	Maximum force produces	5000N
9	Type	Belt carrier

3.4 Robot model Description

The pole type Yamaha cartesian robot model is used for the research work. The cartesian robot model MXY-x type series has been chosen for the research work. They use the technology of 4 row circular arc groove type point contact which helps the robot functions to gain high durability[14]. This means that the robot not going to stop on high pay loads and poor mounting on the base table. This feature provides the low installation surface accuracy to the system. As it uses 4 row circular arc groove type, the system is difficult to break. The robot model comes along with the robot guidance system for object detection and resolver is used for positioning the robot. It has a simple and rigid structure which minimize the use of electronic components.

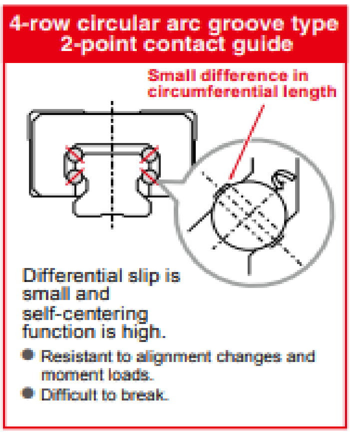


Figure 3.2 Linear mechanism [14]

The robot model is easy for maintenance. Due to its structure, the robot manufacture guarantees the replacement of motor and leadscrew individually. The cartesian robot system uses linear motor mechanism. More about linear motor system can be found in [14]. The ball screw drive motor system of the robot model is shown in figure3.3.

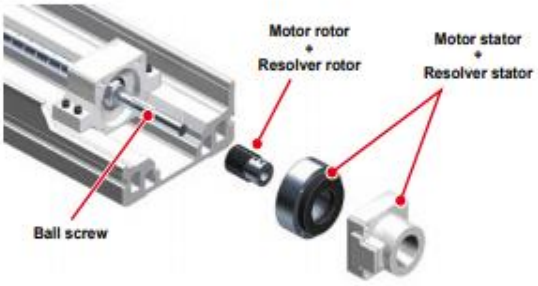


Figure 3.3 Linear motor mechanism [14]

The robot model used for the research work uses cable carrier type model. User cable is provided with the robot model as standard feature. Sagging of the cables won’t happen for this kind of robotic model. The figure 3.5 showing the cable carrier type model. The black coloured cable type is used for this robot model.

Figure 3.4 Pole type cartesian robot system [13]

Figure 3.5 Cable used in robot system [13]

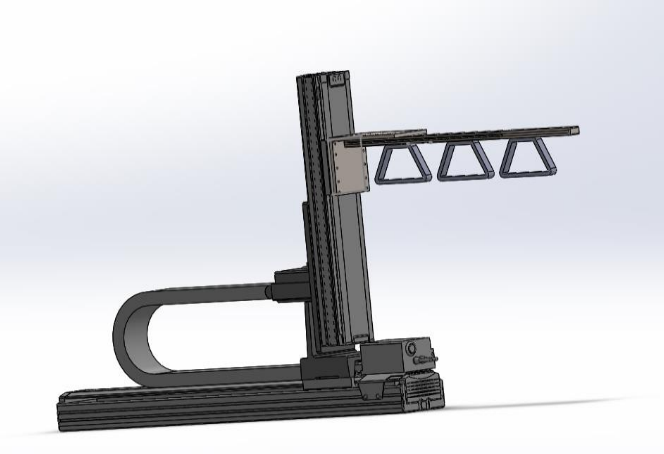


Figure 3.6 CAD model of the selected design and robot

4 FACTORS CONSIDERED FOR DEVICE DEVELOPMENT

4.1 Selection of suitable generator variants

The generators mainly manufactured at ABB are generators for diesel and gas engines, generators for steam and gas turbines, generators for hydro, wave and tidal applications, generators for wind turbines, generators for data centres, Synchronous condensers.

The generator stators using for winding process range from 600mm to 1100mm of outer diameter. The scholar has started the research work including smaller, medium and larger diameter generator stators. The smaller diameter stators are the difficult for the workers to do the insertion process and hammering. The researcher has conducted the theoretical approach of study for the design development of the automated device. The aim for smaller diameter stators had cancelled due to the less room space of the stator. There are two rounds of winding required in every types of generators. Therefore, after first round of the winding, the space inside the stator becomes less and it prevents the free movement of the robotic arm. It has been noticed that, it may further lead to collision of the robotic arm inside the stator frame and on coils as well. This leads to damage of the coils and its insulation. Therefore, the scholar concluded to do the research on larger diameter stators. The main advantages of working with them are, larger room space inside the stator which can leads to the free movement of the robotic arm and insertion process. The main variants of generator stators chosen are 860mm, and 980mm outer diameter frames. These generators can have the number of slots ranging from 42 to 108 depending up on the type of application and customer needs. Since it has a larger diameter frame, the slots width also be bit more compared to smaller stators. Slots width for these stators ranges from 10mm to 24 mm which makes the design development bit convenient for the scholar. The distance between centre of the two nearest slots are given by

Distance between the centre of the slots = 360/Q1, where Q1 is the number slots per machine. There two different inner diameters for the stators.

- Inner diameter D1
- Inner diameter D2

D1 is the inner diameter of the stator between one end of the inner part to other. D2 is the inner diameter of the stator ranging between surface of the slots to another slot’s surface in opposite end.

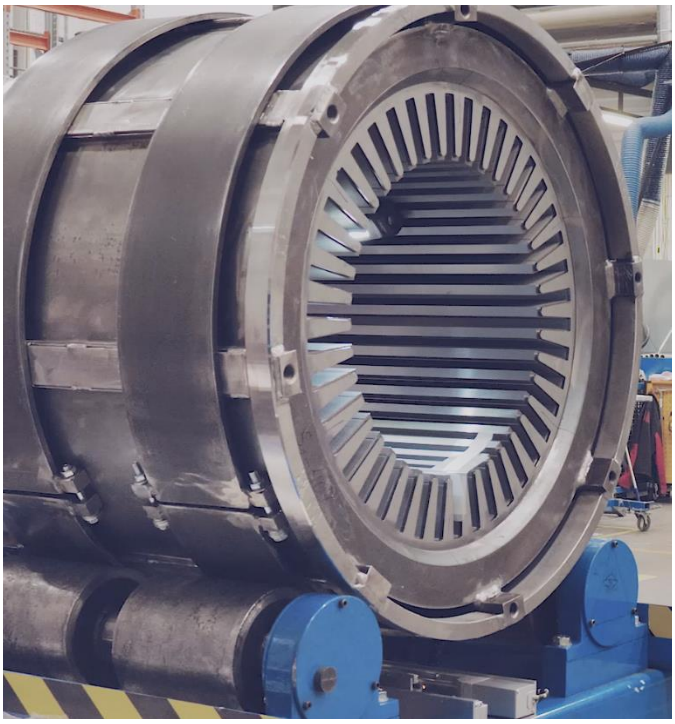


Figure 4.1 Generator stator. Picture taken from factory.

4.1.1 Frame

Generator stator frame is the major part of generator. It consists of an outer layer, inner part where slots are present and outer frame. The generator stators at ABB factory has laminations of silicon steel over it. It is necessary since the voltage is induced by the generator. There are insulations in-between laminations. The stator frame length is determined by the distance between one end to another. The length of the frame processing for winding process ranges from 300mm to 1400mm. The frame has a outer diameter ranges from 600mm to 1100mm.

Table 4.1 Stator data

Inner diameter, D12 (mm)	Outer diameter, D11 (mm)
330	600
365	600
375	680
420	680
465	680
395	680
440	680
420	770
465	770

505	770
480	770
525	770
480	860
540	860
525	860
580	860
575	860
540	980
620	**980**
670	**980**
720	**1100**
730	**1100**
780	**1100**
820	**1100**
850	**1100**

Minimum length of the core is 300mm

Maximum length of the core is 1400mm

The slot width rages between 10mm and 24mm

The selected frame size is highlighted inside the box.

4.1.2 Form coils

Form coils are winding material using in the ABB generators industry for the winding process. Form coils are square or rectangular like magnetic wires. A good level of insulation has been carried out over the coil which in general white or pink coloured the insulation area. The conductive part of the coil always looks black in colour. Wire insulation is designed for operation with three-phase voltages as well as maximum surge or impulse voltages. The coil winding process begins by moving or grinding the magnet wire. The individual turns are placed exactly on each other. The insulation systems are composed of thermosetting materials. They are mica paper treated with polyester or epoxy resin as a bonding material. However, due to random winding, uneven resinous growth is visible in some cases. There is a large opening for the last winding of the form coil, which prevents contamination. Furthermore, the insulating tape on the coil provides additional environmental protection. Tight winding is carried out to reduce the insulation errors.

The coil length varies from 200mm to 1500 in length depending up on the size and type of the generators. The width of the coils varies from 6mm to 20mm. The coils are generally made up of copper.

Figure 4.2 Sample representation of form coil.

4.2 Coil insertion workflow at factory

The workstation majorly consists of working table and the generator stator mounted on it. The generators mainly manufactured are generators for diesel and gas engines, generators for steam and gas turbines, generators for hydro, wave and tidal applications, generators for wind turbines, generators for data centres, Synchronous condensers. The coil type inserting is form coil. For starting the insertion process, make sure that the slots are clean and smooth. After that, verify if there are sharp edges at the end of the straight part. If there, then remove them by filing process. Clean the core with compressed air. Measure sensor readings and fill the control protocol with measured values. Fasten the sensor onto a grooved laminate. Measure the height of the coil and the length of the pressing jaws. The important thing is we need to look up the size of a coil group and mark their position onto the core. For example, stator has seven coils in a group. After selecting the coil pitch, find a most comfortable starting point for coil insertion. The coils should be carried out pressing only on the conductive part. During the insertion process, make sure that the coil is positioned in the centre of the slot. Measure the distance between the end of the active part and end of conductive tape. Then, stretch the top part of the coil at least two slots further than the actual slot where it will be installed. Doing that makes sure the coil will stay in the slot and won’t start sliding out. Place a thin plastic sheet at the end of the top coil which will protect it from insulation damage. For insertion, the coils should be hammered with the help of a rubber hammer. After finishing the first level of winding process, pick the proper wedges for wedging process. Cut the strips of felt about 2 to 4 millimetres longer than the wedge and install them to required places. Support rope should be cut based on required length. By using a measuring tool, the internal dimension has been recorded and external dimension also. The rope is using to tie the coils together for inserting the sensors. The sensors are placed into marked slots. Make sure that the sensor cables run between same phase coils.

Figure 4.3 and figure 4.4 represents the schematic and process flow chart of the existing coil insertion process respectively.

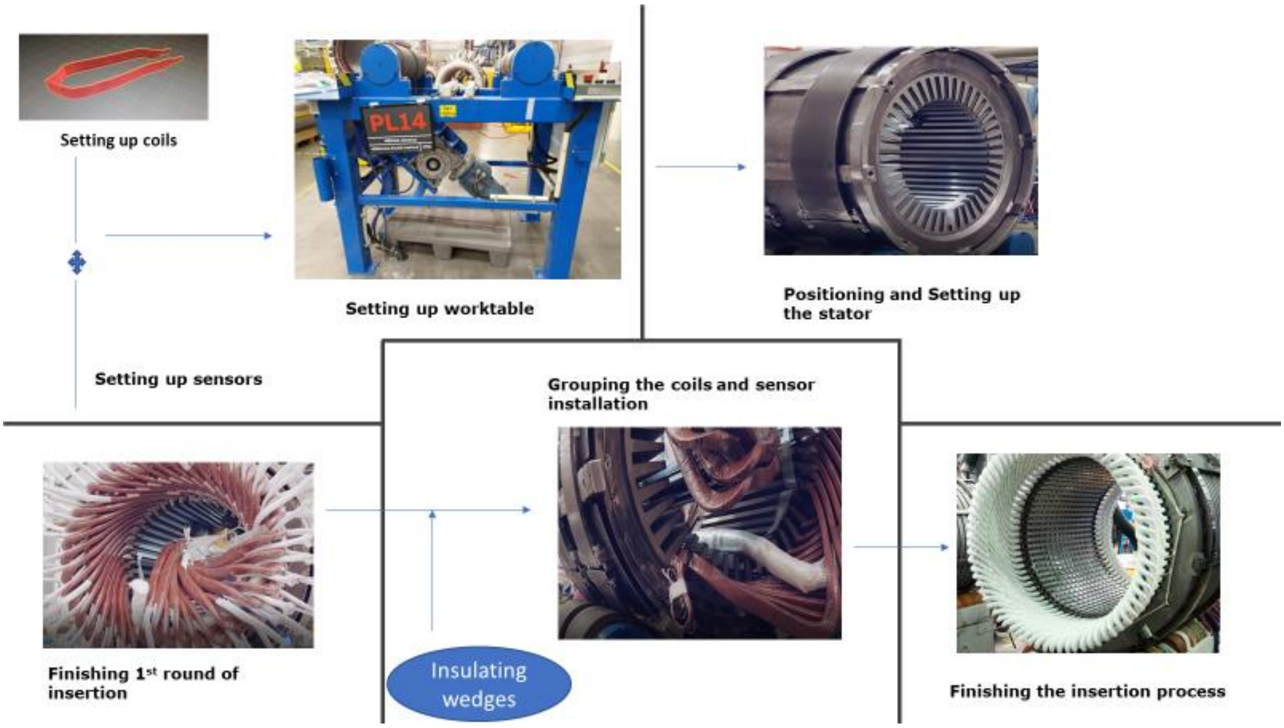


Figure 4.3 Schematic of existing factory workflow

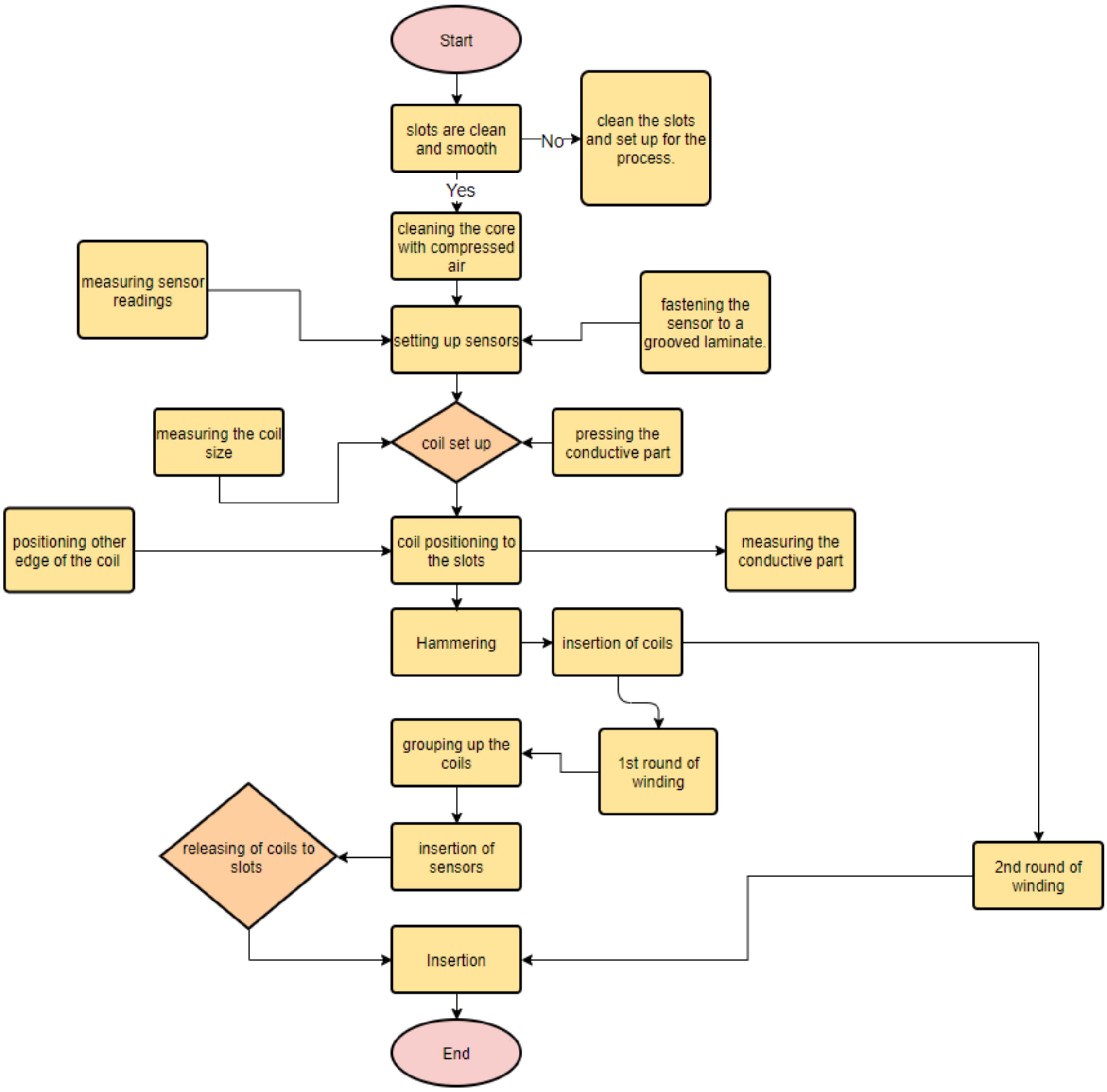


Figure 4.4 Factory workflow process diagram

4.3 Workforce calculation

4.3.1 Theoretical approach for workforce calculation

It is very important to measure and calculate manual force exertion on coils during hammering process. Currently workers are inserting coils by manual hammering using rubber mallets. The researcher approached the following method to calculate the force exerted during manual hammering. The normal speed of human hand movement during hammering is 10m/s to 15 m/s depends on the size of the coil and width of the slots. This research is majorly focused on larger diameter generator slots and therefore hammering need to be done on larger coils, the researcher opted for hammering speed of 10m/s. Mass of the mallet varies from 1Kg to 2 Kg. Here it is chosen 1Kg of mallet. Theoretically approached equation for the manual force calculation is given below,

$$\text{Impulse on the coil} = mv - mu \tag{4.1}$$

Where v as final velocity and u as initial velocity. Initial velocity of coil is taken as zero and final velocity is 10m/s after the impact of mallet, m is the mass of the mallet.

From equation 4.1, impulse = (1 X 10) – 0 = 10Ns.

After hammer hitting on the coil, it transfers this energy to the coils in order to fit inside the slot. Therefore, magnitude of the force acting on the coil is given by

$$I = F \times t \tag{4.2}$$

Where t, is the time required to take the mallet comes to rest after hammering. This has been measured using stopwatch by a series of repetition and average has been taken as 0.0045 seconds. It means, after 0.0045 seconds the mallet comes to rest. From equation 4.2, $10 = F \times 0.0045$

$$F = I / \text{time} \tag{4.3}$$

$$\text{So, force} = 10 / 0.0045 \tag{4.3}$$

$$\text{i.e.) force} = 2222.22 \text{ N}$$

So, it defines that, 2222.22 N of hammering force is required for moving the coil in larger diameter generator stators. The above calculated value is not practical. It doesn’t give any exact idea about the coil movement level and distance. This is an assumption made for the theoretical approach. Therefore, the practical test has followed as described in next content.

4.3.2 Force measurement using force gauge

For the insertion of the coil, it is very necessary to know the data about force exertion. More specifically, the force exerted during the human coil insertion process is very important to record and collect. The researcher discussed the method and already collected force data from the industry engineer which is approved by the company level. The method for force calculation was conducted by placing the sensor code (also known as force resistor) on the coil. It was critical to know the minimum force required and the maximum force required for an efficient device development. Therefore, the coils selected for testing varies from smaller to larger size. The method of force calculation was conducted by digital measuring force gauge. The labours were instructed to hammer on the surface area of the coils where force sensor code has been placed which was further connected to the digital force gauge. Five random workers were selected for testing in order to determine the force exertion possible from labours with different physique. The same testing criteria had opted for larger size coils. Since this research work is focused on larger diameter stator coil insertion process, the maximum force exertion is much required. The average of the measured values was accepted and approved by the industry. The accepted force measurements are given below,

The minimum amount of force measured = 108N.
The maximum amount of force measured = 2700N.

The above specified values are already in use at the industry level. These values have been followed up for the device design and development. The scholar gathered the technical method of the force measurement and testing shared by the production engineer in charge from the industry side. These values vary from smaller to larger diameter stators. The minimum values represent force for smaller diameter stators while maximum values recorded for larger diameter generator stator. Using these measurements, it is very important to set up the force limit in robot cell.

4.4 Calculation of Robot working space

The robot working space area calculation is very important for the design part of this research paper. This calculation figures out the estimation about the desired design development of the device and tool components. To make sure about the calculation, researcher has selected a generator stator with an inner diameter of 820mm and 1100mm of frame length. Working space has been chosen as the space available inside the stator at free state of the generator. Free state of the generator is the empty frame of the generator without any kind of winding inside the slots. The working space of free state stator is shown is figure 4.5. The red coloured space is the available area and is equal to area inside the stator. It necessary to calculate the inner area, total hight available inside the stator, and total distance available to move towards left and right.

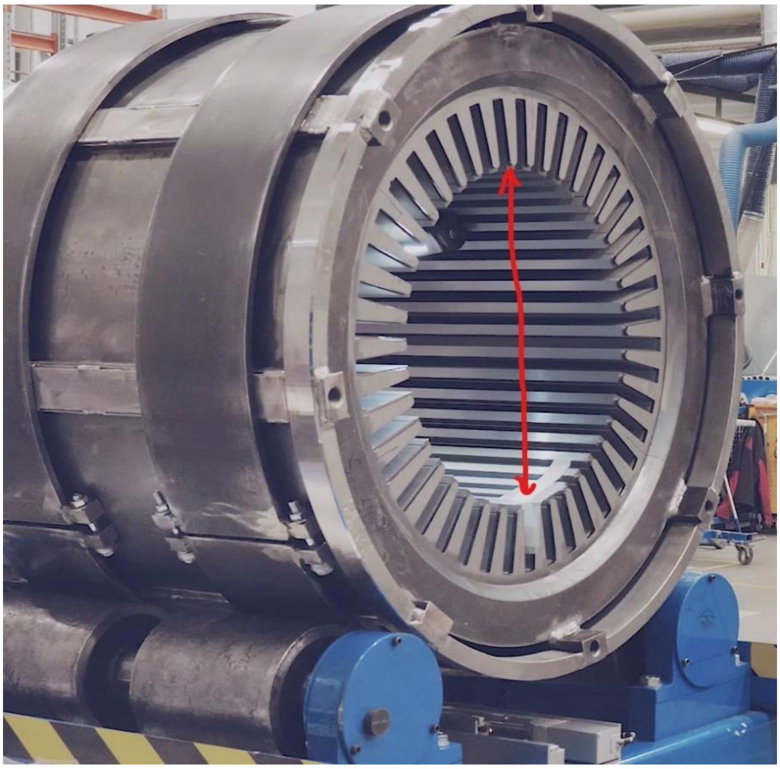


Figure 4.5 Working space of the robotic arm.

$$\text{Inner surface area of the cylinder} = 2\Pi rh \times 10^{-6}\ m^2 \quad (4.4)$$

Where r is radius of the stator, h is equal to hight. (here length is taken as h as it is in hollow cylindrical shape) and $\Pi = 3.14$

Therefore, from equation 5.1,

$$\text{inner surface area} = 2 \times 3.14 \times (820/2) \times 1100 \times 10^{-6}\ m^2$$

$$\text{inner surface area} = 2.832 m^2.$$

Surface area of the circular face (side marked with red colour in figure 5)

$$\text{Area} = \Pi r^2 \times 10^{-6}\ m^2 \quad (4.5)$$

$$\text{Therefore, area} = 3.14 \times (820/2)^2 \times 10^{-6}\ m^2$$

$$= 0.527 m^2.$$

The space occurred by the robot and device set up should be able to occupy lower area than the above values. Therefore, the estimation for the total area of occupancy by the device set up was calculated with the following assumptions.

- Length of the insertion tool device should not exceed the total length of the stator frame
- Size of the insertion part dimensions not exceedingly more than 650mm X 100mm X 23mm as length X hight X thickness respectively.
- Total hight occupied not exceeding the 80% of the inner diameter of stator.

4.4.1 Sensing and calculation

The researching generator stator diameters ranging from 800mm to 1200mm. Therefore, the sensor should be able to read and record each and every locations and points of the inner side of the stator core. For this purpose, it requires a good level of light source and sensing resolution. The test stator has a length of 1000 mm in length and has an inner diameter of 720 mm in length. So, the end localised sensor should be able to read the parts within the range of at least 350mm x 250mm as length X width respectively. The scholar has recorded the measurements of the required sensing area of the inner stator part which is almost similar to above measurements. To determine the centimetres from the pixels, the scholar has chosen the following equation,

$$\text{centimetres} = \text{pixels} * 2.54 / 96 \tag{4.6}$$

Here the equation will become as,

$$1600*2.54/96 = 42.33 \text{ cm}$$

which is nearly equals to 42. So, the length is 42 cm.

$$\text{Width} = 1200*2.54/96 = 31.75 \text{ cm.}$$

Therefore, the sensor range is 420mm X 317.5mm as length X width respectively. This sensor range is covering the required working space for the sensing range. The workstation consists of a working table with an adjustable rotating part and a shelf of all other required specimens and parts. Since the working area is very simple and less space, the presence of an additional worker for monitoring the sensor will be a disadvantage for the work process.

5 DESIGN DEVELOPMENTS

5.1 Selection of the design and analysis

For the research work developments, the scholar has developed the majorly three types of designs as shown in following figures.

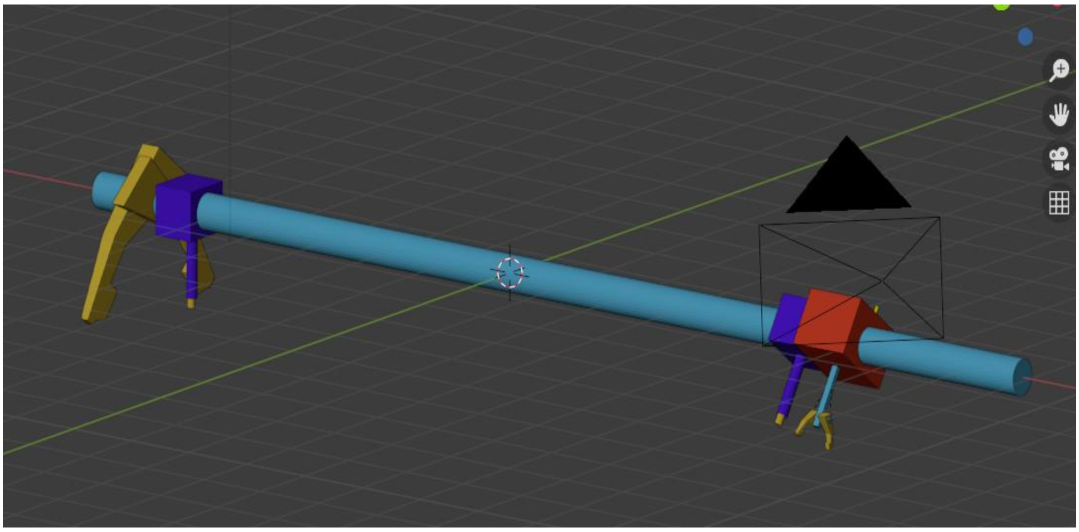


Figure 5.1 Representation of design 1

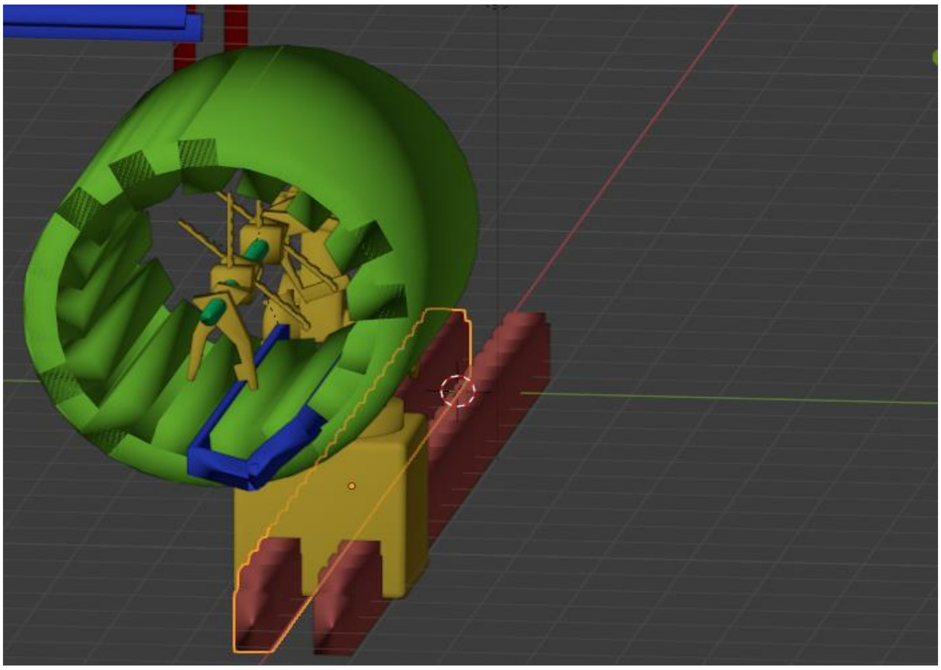


Figure 5.2 Insertion process of design 1

A short description of the mechanism of design 1 has been given below.

There two types of grippers developed by the scholar. Frontline grippers and backend grippers. The front-line grippers are fixed at the end part of the tool frame which has a thickness ranges between 40mm to 80mm and downward grasping finger length of 100mm to 200mm. Backend grippers are fixed at the end where tool frame has been connected to robotic arm. They are very thin compared to frontline grippers. Their thickness ranges from 20mm to 50mm and downward grasping finger length of 100mm to 150mm. Two gripper fingers are assumed as one pair of grippers. Electrical linear actuators are adjusted very next to the grippers. They will push and insert the coils into slots.

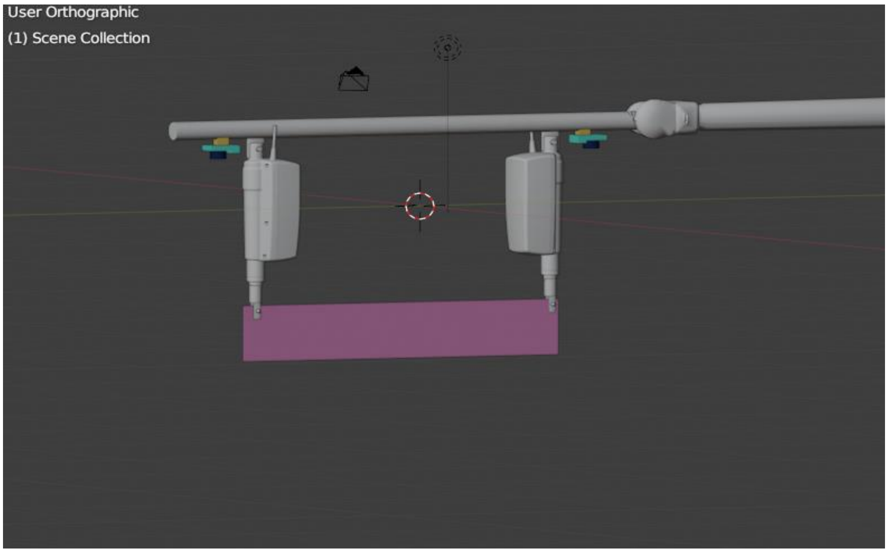


Figure 5.3 Representation of the design 2

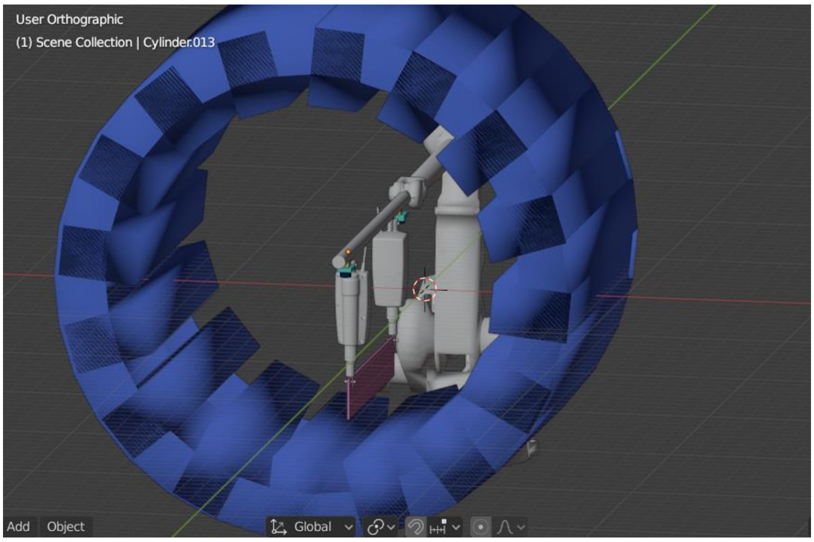


Figure 5.4 Insertion process of design 2

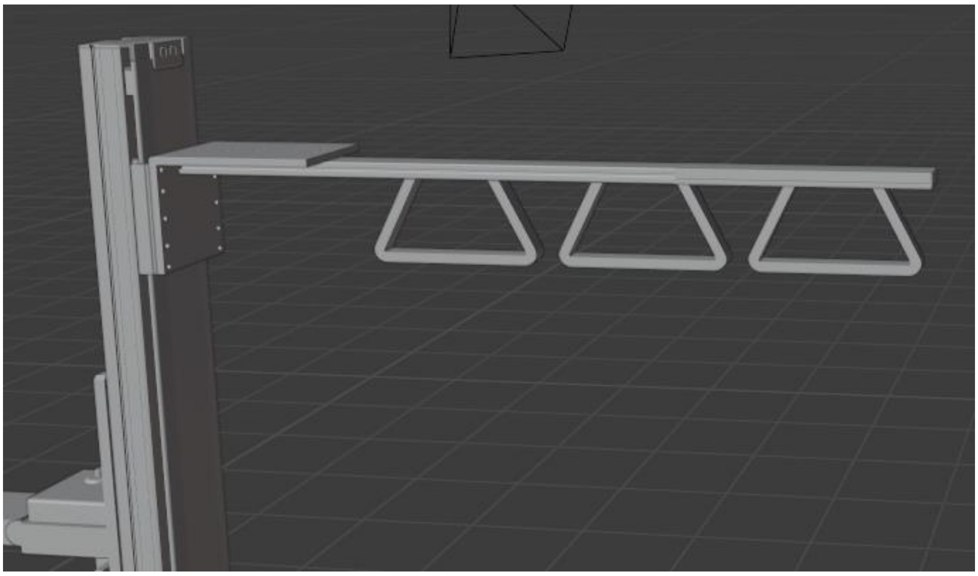


Figure 5.5 Representation of design 3

Based on those characteristics, a comparison has made and listed below in table.

Table 5.1 comparison between three developed designs

	Design 1	Design 2	Design 3
Functions			
Shape of the insertion part	Finger like grippers are used for insertion	Flat rectangular structure is used for insertion	Trapezoidal
Insertion process	Integrated fingers simultaneously insert the coil	Flat rectangular part inserts with the help of actuators	Trapezoidal insertion part does the work
parts	Insertion frame, finger like inserting parts, actuators	Actuators, connectors, insertion frame, insertion portion	Inserting portion and frame only
connections	Using welding, nut and bolts	More welding and connector frame. Nut and bolt used for mounting	Only mounting screws are used.
Robot type used	Articulated type	Articulated type	X-Y type cartesian robot
Robot reachability inside the stator	700-850mm	700-900mm	2 number of robots used. Maximum reach inside is 1000mm
Static analysis	Not impressive results	Better results but chance for collision and break down	Good results

Below table shows the layout of the technical comparison between three designs. Those are more important since it depends the further developments and simulations.

Table 5.2 Technical specifications

Technical specification	Design 1	Design2	Design 3
Dimensions of the insertion part in mm	100 X 30 X 15	500 X 100 X 20	180x30x10
Weight (insertion part only)	Maximum 4 Kg	Maximum 8 Kg	Maximum 2 Kg
FEA analysis – stress in N/m^2	9.560+05	7.120e+05	4.317e+03
strain	15.869e-05	8.538e-06	1.476e-08
Displacement of the frame in mm	2	3	1.2

Other main technical drawbacks of the design 1 and 2 are reasoned in detailed below,

- The robotic tool become failure when it comes to the application for smaller diameter stator winding.
- During the winding process, after the 1st round of winding, the room space inside the stator reduces as a result which restrict the free movement of robotic arm and may chance for collision to stator and coils are high.
- For larger diameter, the coils are also bigger in length and weight. Also, the gap between one side to other side is high.
- These problems created the requirements of extra pairs of more grippers on the tool frame which is capable to lift bigger coils.
- Picking the coils and inserting them into slots become impossible due to these challenges and create another necessity of the re-design. During the insertion, need to set the maximum force limit to the robot cell in order to carry out a safer manufacturing process. So, the need for extra device has been arises
- The finger grippers not able to lift the coils since coils are weighing from 5 kilograms to 20 kilograms.
- The gap between one side to other side of the coil varies from 100mm to 500mm.
- For lifting the bigger size coils, the grippers should be more tough and durable and need more pairs of grippers on tool part.

- The need for more pairs of grippers created another necessity for developing a second robotic tool frame which is completely impossible here.
- The width of the slots varies from 6mm to 24mm.
- This created the requirement for thin pushers capable to operate with in the slot width range.
- Pushers are assumed to be combining the gripper fingers together. In order to make a thin pusher, the grippers also should be very thin which would result in breaking of the grippers.

From the above two tables it is clear that design 3 is better and better. Therefore, the researcher decided to go ahead with further developments with cartesian robot system. For the insertion part, the scholar has decided to choose two types of design options: rectangular shape and trapezoidal shape. The comparison is listed below in table.

Table 5.3 Comparison between insertion part designs

Trapezoidal shape	Rectangular shape
The length of the single part is 400mm in total which has 2 insertion portions.	The length of the insertion part is 500mm which makes the necessity of insertion frame should be at least 700mm
Maximum displacement occurred on the insertion part is 3.213e-06mm	Maximum displacement occurred on the insertion part is 1.479mm
Maximum displacement occurred on the insertion frame is 1 mm	Maximum displacement occurred on the insertion frame is nearly 2.5 mm
Good stress analysis results	Bad results compared to trapezoidal shape
Room space occupancy inside the generator stator is nearly 50%	Room space occupancy is more than 50%
Mounting is done by screws	Mounting needs extra welding
No need of any extra connecting frame or structures for mounting to the insertion frame. only screws needed	Connecting structures are required since it has many joints compared to trapezoidal shape.
No need of nut and bolt	Nut and bolt is required for mounting to the actuators and frame
Simple structure	Makes it bit complex due to welding and connectors.

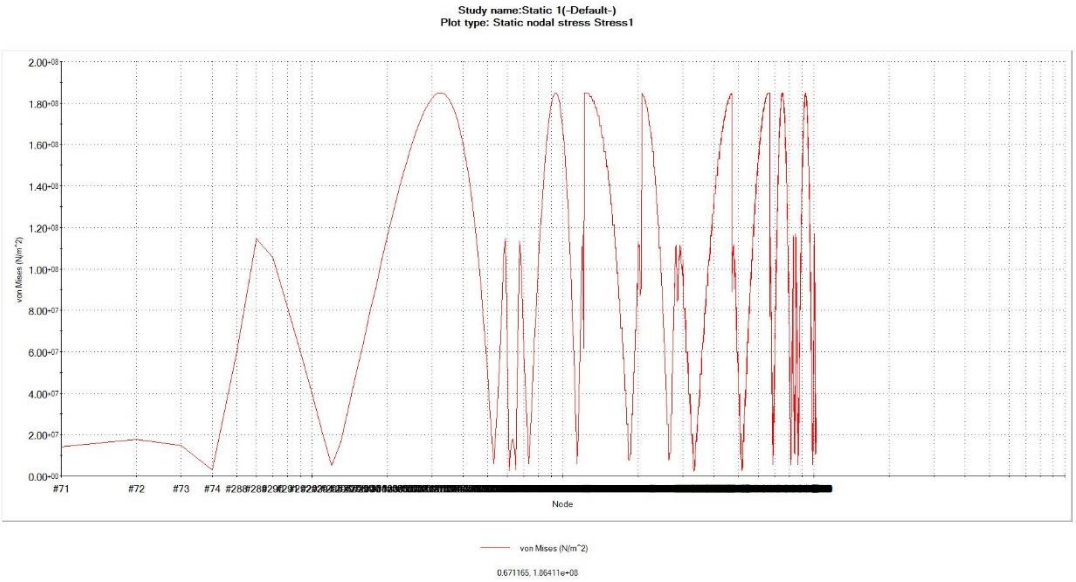


Figure 5.5 Stress on rectangular shaped insertion part. Developed in solidworks

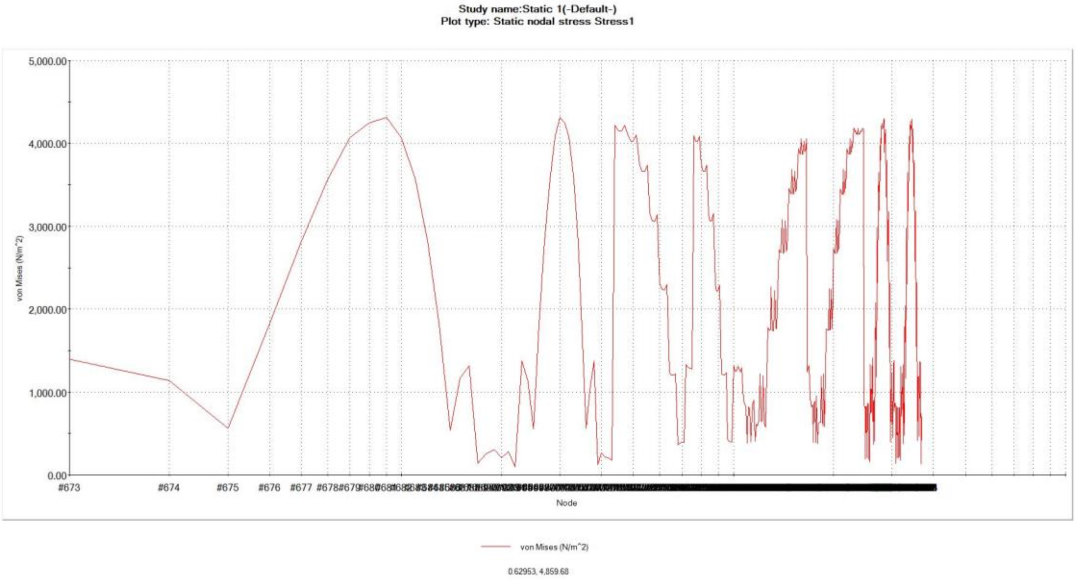


Figure 5.6 Stress on trapezoidal shaped insertion part. Developed in solidworks

From the above table and graphs, it is clear that trapezoidal shaped insertion part is more suitable for the design. As mentioned in the table, the rectangular part requires more welding joints and connectors to attach on the frame which makes the system more complicated. For the trapezoidal design, it can be mounted with just screws. Also, stress for rectangular shaped design is 1.851e+08 N/m^2 and for trapezoidal part is just 4.317e+03 N/m^2.

5.2 Material selection

5.2.1 Alloy steel S316

Alloy steel is majorly used material throughout the design development. This has been used for frame, insertion part and connector.

Table 5.4 Alloy steel S316 composition [20]

Element	Amount in %	Benefits
Nickel	12-20	Increases strength and prevents corrosion
chromium	4-18	Toughener
Molybdenum	0.2-5	Increases toughness of the material
Silicon	0.2-2	Improves magnetic functions
Manganese	0.25-2	Reduce brittleness
copper	0.1 -0.4	Resist corrosion
Boron	0.001-0.003	Hardening
Vanadium	0.15-0.20	Toughness at high temperature
Aluminium	0.1-1.5	Alloying element
Properties		
Elastic Modulus	2.10e+11 N/m^2	
Yield Strength	620421997.8 N/m^2	
Poisson's Ratio	0.28	
Tensile Strength	723825617 N/m^2	
Thermal Expansion Coefficient	1.3e-05 K	
Mass Density	7700.000118 kg/m^3	

5.2.2 Aluminium 6061

Aluminium 6061 has been used for the robot moving platform. The material composition has been given below.

Table 3.5 Aluminium 6061 composition [19]

Element	Amount in %	Benefits
Aluminium	Balanced	High yield strength
Magnesium	0.80-1.20	Anti-corrosion
Silicon	0.40-0.80	Improves functions
Iron	0.70 maximum	Alloying agent
Copper	0.15-0.40	Anti-corrosion
Chromium	0.04-0.35	Toughener
Zinc	0.25 maximum	Alloying agent
Titanium	0.15 maximum	Alloying agent
Manganese	0.15 maximum	Reduces brittleness
Other	0.15 maximum	Improves structural functions and as alloying agents
Properties		
Elastic Modulus	6.9e+10 N/m^2	
Poisson's Ratio	0.33	
Shear Modulus	2.6e+10 N/m^2	
Mass Density	2700 kg/m^3	
Tensile Strength	124084000 N/m^2	

5.3 Developed device design parts and components

5.3.1 Yamaha X-Y pole type cartesian robot system

The coil insertion device is developed based on the principles of cartesian robot. The researcher has followed the XY type cartesian robot type. The researcher developed the proposed device by assembling the robotic parts available from the Yamaha robots manufacturers. More clearly, this automatic device is assembled and developed for the desired research work. For the easy understanding of the model, the whole model has been divided as Parent robot, Job arm, and Insertion part. The figure 5.7 below shows the parent robot. It means that this part hold and assembly the Job arm and Insertion part.

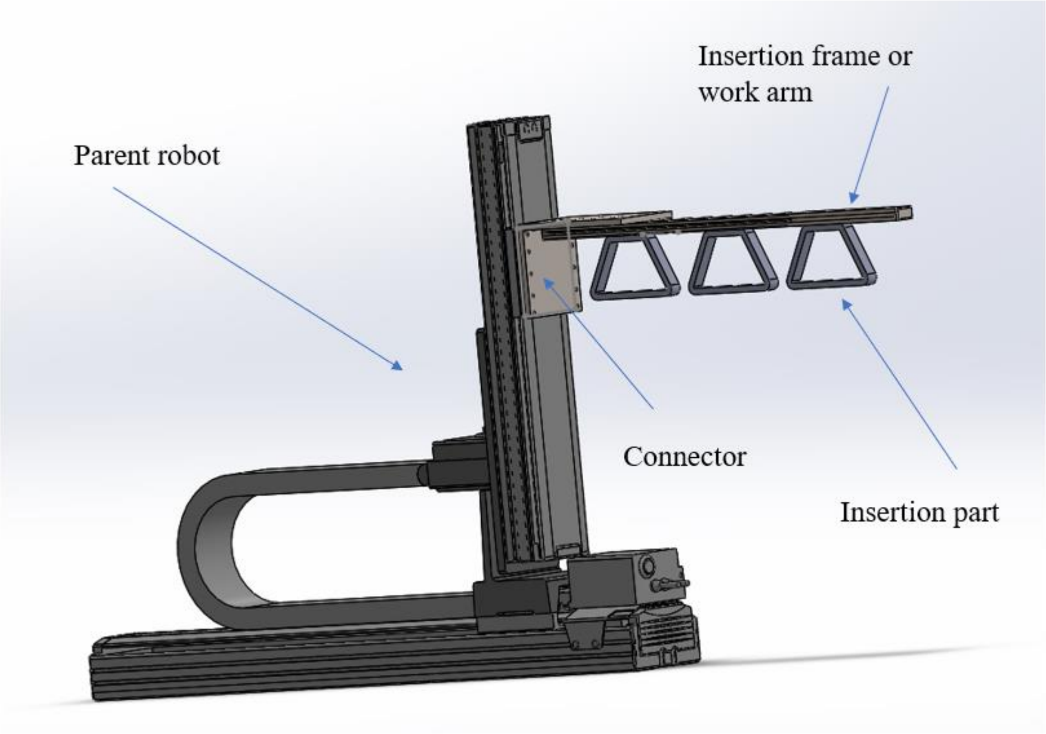


Figure 5.7 CAD model of the robot assembly system

The figures 5.11 and 5.12 represents the work arm and insertion part respectively. X axis is fixed on a table or platform to fix the robotic frame. This can be done with the help of mounting screws available from the Yamaha manufacturer. The robotic frame is made up of steel alloy which makes the structure strong and rigid. More details regarding the Parent robot can be found from [12],[14]. Assembly sketch has been defined under appendix 1. X axis stroke is 750 mm and Y axis stroke is 650mm in length respectively. The robot has a cable carrier which is able to move with respect to Y axis along X axis frame.

5.3.2 Robot slider

The robot slider is the major component mounted on parent robot. The figure 5.8 below shows the robot slider. It can move along the desired directions regarding the power transmission. Also, its front side is able to hold or provide the surface area for mounting the robot branches and other components. The holes visible on the surface are for mounting screws and the size of the holes varies with respect to the size of the robot conveyor and applications. In this research the corresponding mounting screw holes are of 6mm diameter.

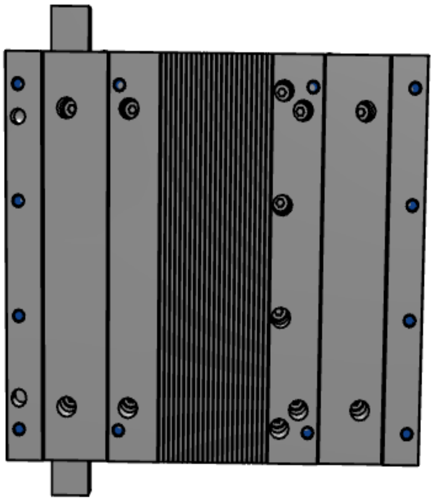


Figure 5.8 Robot slider [14]

The figure 5.9 below shows the bottom part of the robot slider. It has four blocks represented as A, B,C,D which are the moving blocks and helps to interlock on the moving track. Both sides, 1&2 from the picture, are the holding sections of the robot slider which provide a rigid support. This has been fixed and mounted by pushing inside the sides 1&2 into the linear conveyor, clearly on Y axis.

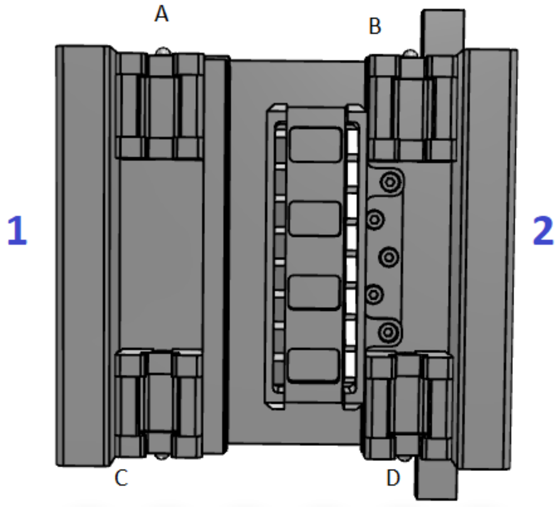


Figure 5.9 Bottom view of the robot slider [14]

5.3.3 Work arm

Work arm is the robotic arm part where the insertion part is attached. This is a type cartesian robot part and it's insertion part attached is functioning as x axis part on Y axis. Job arm is attached to the Y axis of the parent robot with the help of Job arm connector. Job arm connector is shown in figure This is made up of steel alloy material and the connector attached to the robot slider by mounting screws. This connector is in inverted 'L' shape and attaching the insertion part as well. 10 number of screws holes are provided on the surface where it comes in contact with the connector for mounting. The job arm provide the enough force for the insertion process.

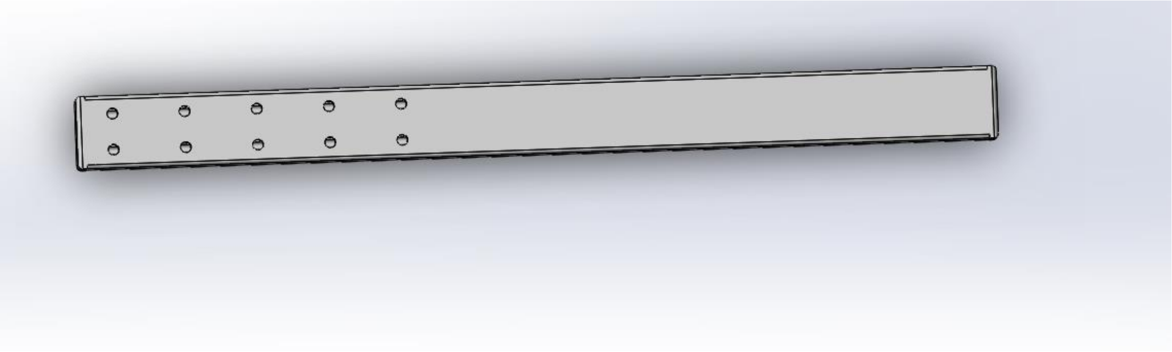


Figure 5.10 Frame view attaching to the connector

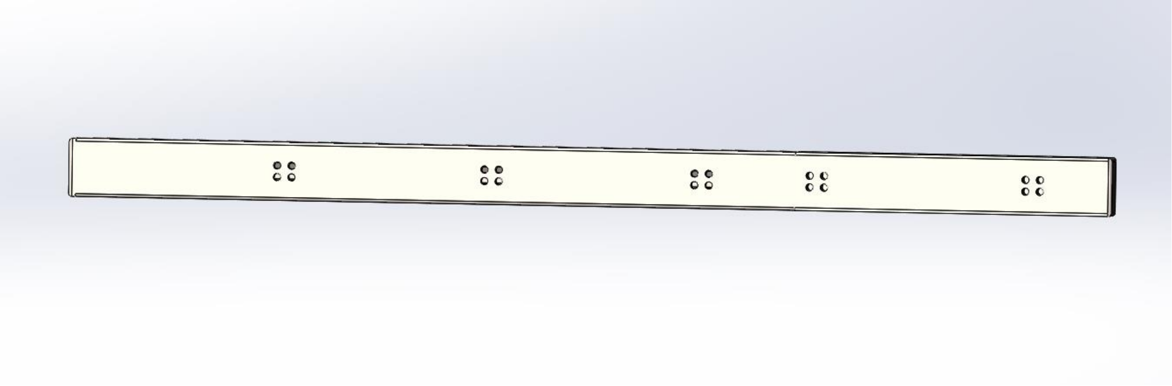


Figure 5.11 Frame view attaching to the insertion part

Dimensions = 720mm x 40mm x 20 mm

Material = Steel alloy

Weight of the frame = 2.58Kg

5.3.4 Insertion part

This is the vital part in this research work and obviously of the robot model as well. Insertion part contains majorly an insertion frame, insertion end effectors. The detailed representation is given below in figure 5.12. The insertion frame is 300mm in length and the insertion end effectors are 20 mm in length. The end effectors are attached to the frame by two supporting legs which are welded and integrated with insertion frame. End effectors are 5 in number for the entire frame length and each end effector is fixed 20mm apart from previous. The end effector surface width is 15mm and thickness is 10mm. The detailed drawing is shown under appendix 3. This has been designed in-order to avoid the occurrence of frame fracture or bending at any point due to the reaction force during the coil insertion. The support is made up of steel material. The supporting bar is attached to the Y axis of the cartesian robot slider which helps the supporting bar to make up-down movements with respect to job arm.

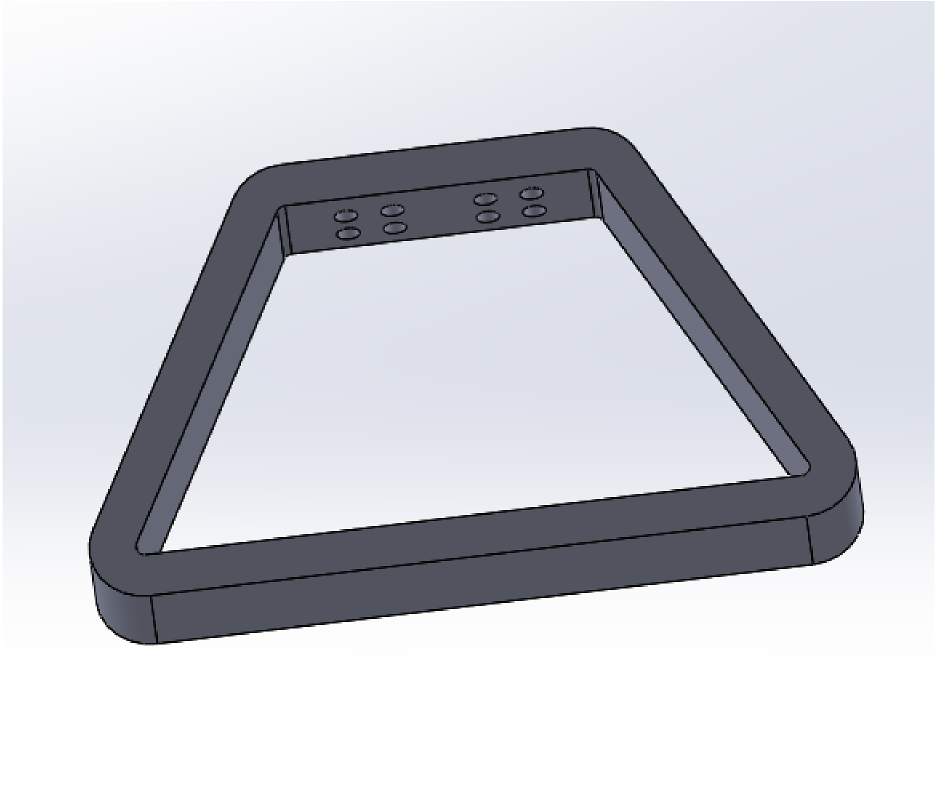


Figure 5.12 CAD view Insertion part

Weight = 1.55 Kg

Material = Steel alloy

5.3.5 Job arm connector

The figure 5.13 represents the frame connector. The purpose of this part is to connect the entire insertion frame to the parent robot. The connector mounted on the surface available on the robot slider. It is mounted using 6mm diameter mounting screws. They are also same as the other robotic mounting screws used for the entire cartesian robot system. 10 number of screw holes are provided on the surface for fixing where it comes in contact with insertion part frame and 10 numbers on the surface where it comes in contact with the robot slider.The details of the mounting screws can be found from [13]. The drawing details are given under appendix 2.

Weight of the part = 3.45 Kg

Material = Steel alloy

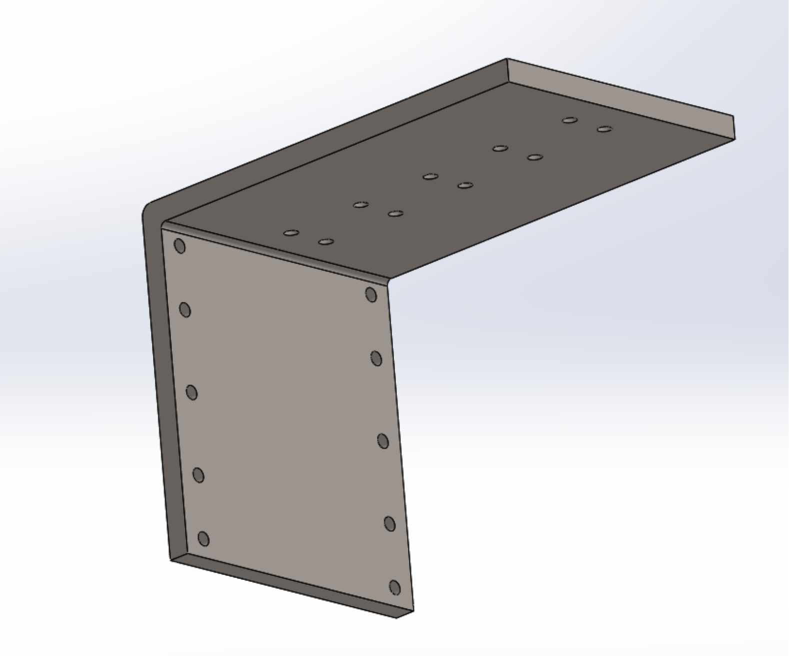


Figure 5.13 Robot frame connector

5.4 FEM analysis

Finite element analysis has been carried out for the designed parts and components. The solidworks simulation is utilized for the FEM analysis of the components. The analysis was done majorly for the insertion end part and frame – insertion end part assembly.

5.4.1 Insertion part

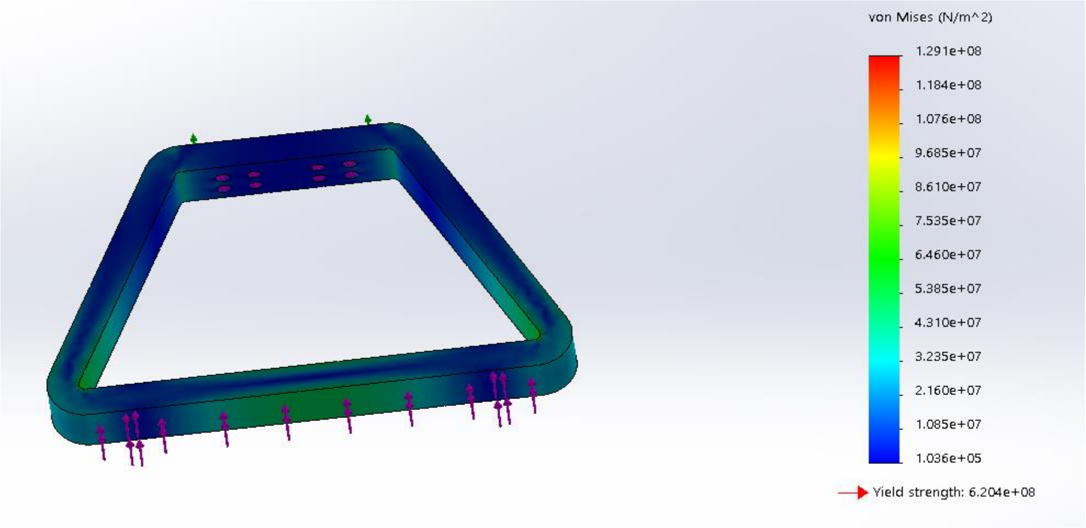


Figure 5.14 FEM stress analysis of insertion part

The result mentioned in figure 5.14 defines the yield strength for the insertion end part. The material used for the design is steel alloy and the yield strength is given as 6.204e+08. For the analysis the applied force is taken as 3000N since the maximum force measured for the coil insertion is 2700N. The screwing surfaces are made fixed surface. The maximum stress resulted for this part is 4.317e+03 N/m^2. This value is safe for the designed model components. The force is also applied to the screwing holes as shown in figure 5.15. The stress value maximum is same and the design seems to be more strong over those areas.

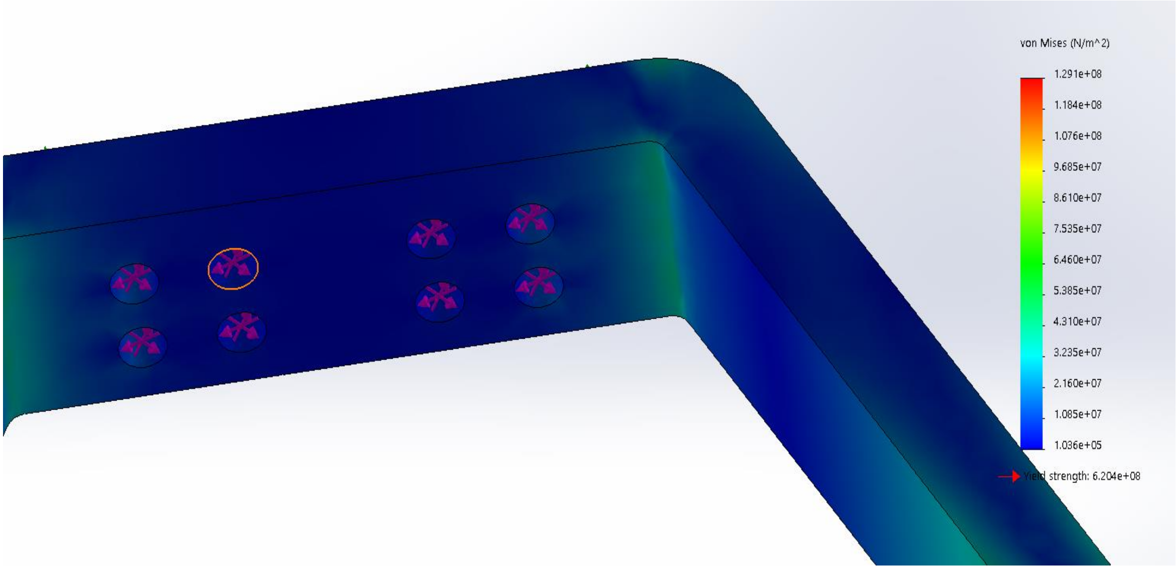


Figure 5.15 FEM analysis on screw holes

5.4.2 Frame and insertion part assembly

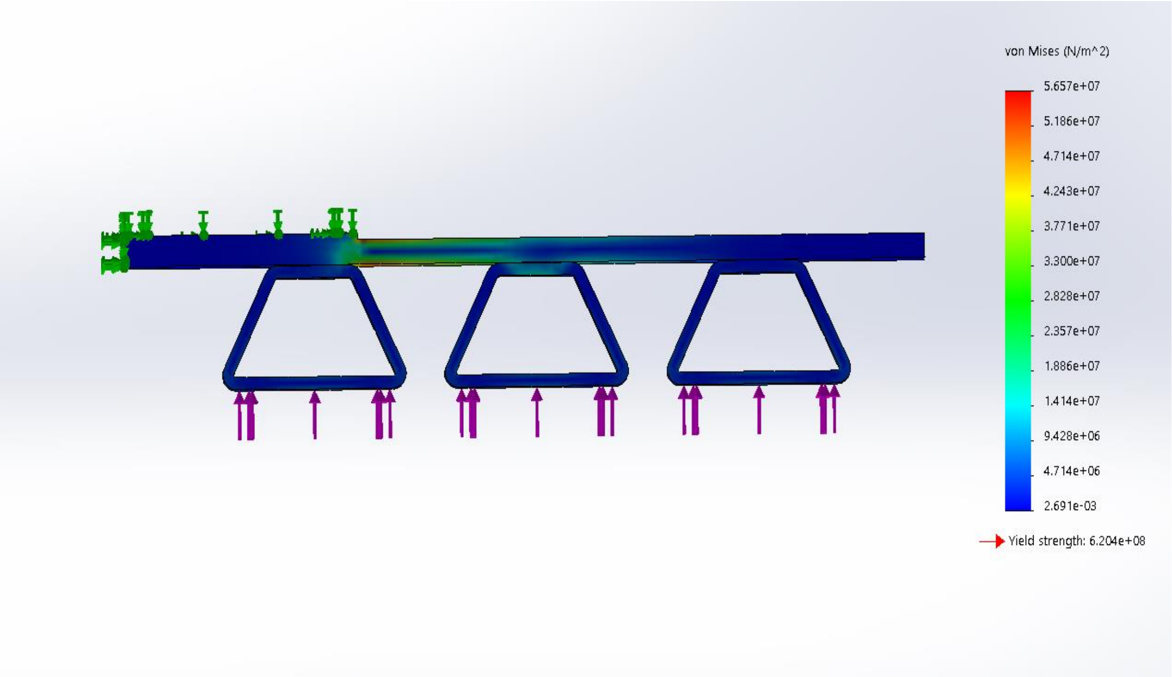


Figure 5.16 FEM analysis on insertion frame assembly

The FEM stress analysis of the insertion frame assembly in shown in figure 5.11. The assembly is subjected to a maximum force of 3000N. The material for the whole assembly is steel alloy. The area surfaces where it is attached to the frame connector chosen as fixed geometry. The force is applied as shown above. The maximum stress occurred for the frame is 1.541e+08 N/m^2. The assembly system is safe and strong under the maximum force application. The static displacement of the assembly under same conditions are given below in figure 5.16. The maximum displacement occurred for the system is 1.178e+00 mm which is negligible.

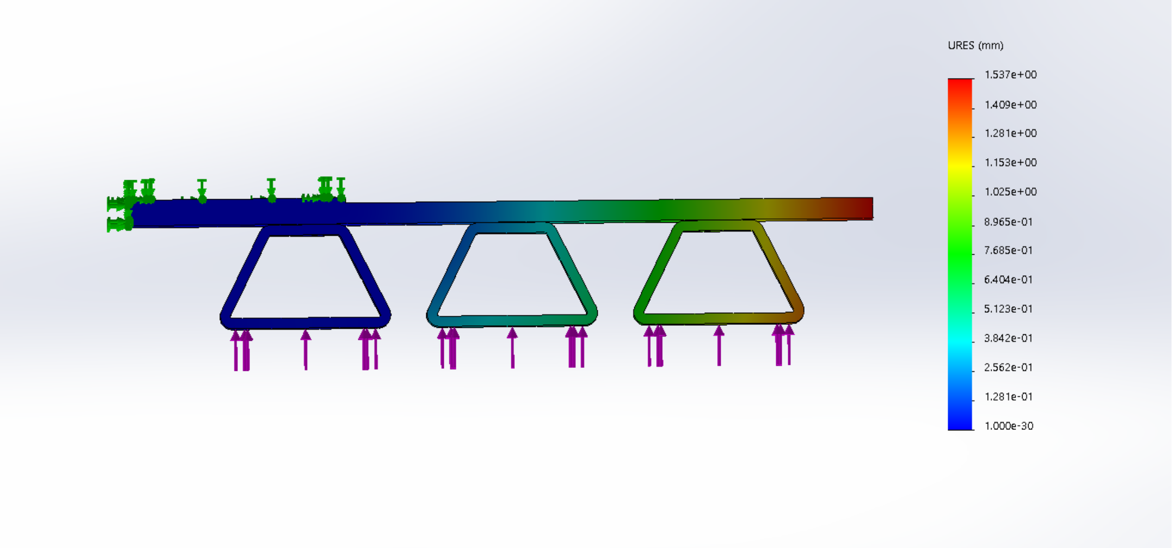


Figure 5.17 Static displacement of insertion frame assembly

5.4.3 Frame connector

The result in figure 5.12 shows the analysis done for the connector part.

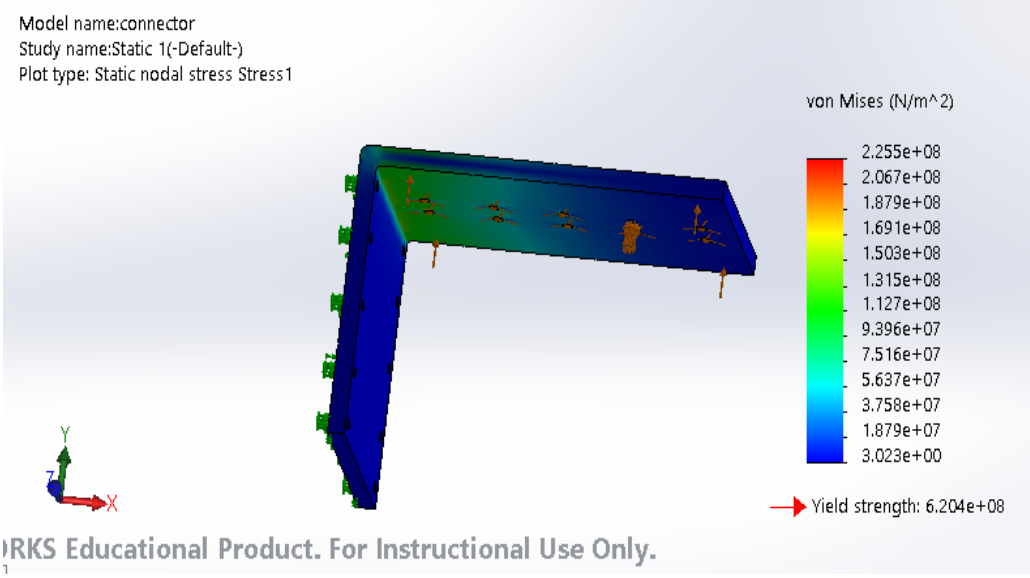


Figure 5.18 Stress analysis for connector

The surface where the connector mounted on the robot slider is made as fixed geometry and force of 3000N has been applied to the surface where it faces the frame. The resulted stress is 2.225e+08 N/m^2 which is a safe value for the design. The displacement for the structure under same test condition is 1.347e+00 mm which can be neglected here. The result is shown in figure 5.19

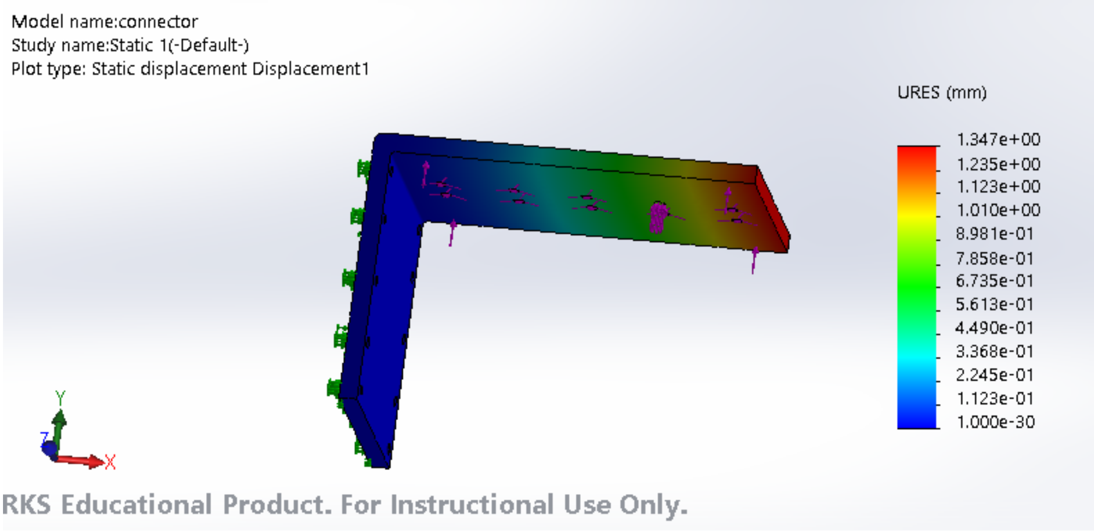


Figure 5.19 Static displacement of connector

5.5 Working mechanism

The proposed device set up is designed for making coil insertion more efficient and effective. The device is designed for insertion process only. The generator stator need to set up for the insertion process as mentioned under chapter 4.2. The Yamaha MXYx cartesian robot system move towards the work point , 750mm , and positioned at that point. The positioning of the robotic arm is completed by the help of a pair of Yamaha robotic sensing system. This is available in [11]. The robotic movement inside the stator is guided by these sensor systems. S1 stands for sensor system of robot1 and it leads the robotic tool towards the surface of the stator until the sensor system detects the inside pre-defined coil insertion area. On the other side, S2 (sensor system of robot2) detects the coil presence by same procedure. Black colour is the conducting part of the coil where the insertion tool comes in touch. Once the S1 and S2 detects their respective target inside the stator which is the conductive part, these data recordings transferred to sensor software which is integrated with the robotic cell. The technical details of the sensor are justified in [11]. After positing the robotic arm, S1 and S2 start focusing on conducting part which is normally black in colour in order to adjust and align the insertion tool over the insertion area. Once this process finish, the robotic arm positioned at that point and robotic cell send the command for the insertion process. Insertion part pushes the coil with the help of integrated insertion part at a required force range.

The main sensitive part of this insertion process is the force controlling. If the force limit exceeds, it might cause the damage to the coil and insulation. Therefore, a controlling system is implemented to the mechanism. A force resistor system is used to measure the force exertion. The maximum limit is defined as 3000N in the robotic cell and if it records the limit then robot end its operation. For larger diameter stator winding process, the recorded maximum force is 2700N. Therefore, keeping the force limit 2800N is suitable for achieving the efficient insertion process. The author has discussed the principle and working set up with the industry engineer for more precise mechanism development.

After first round of winding process the process repeats for the other coil. The insulation wedges and coil sensors are placed manually regarding the respective manner.

5.5.1 Alignment of the robot

The robots have to be aligned over the stator core with respect to the robot kinematics. The Yamaha robot simulation and support software available from the manufacturer has been used for it. The software allows the robotic arm to move and position itself inside the desired workspace. The proposed alignment of the robot also depends and influences the mounting table, size of the stator, coil, and insertion tool part.

As per the manual form coil winding process, the exact position of the slots has to be defined and need to follow that for the coil insertion. After placing the coil over the defined slot position by manually, the robot inserts the coil into slots. It means the insertion tool part moves into the slots. The slots width could be ranging from 10 mm to 24 mm. Therefore, the available clearance for the insertion part is limited and thus designed with in this slot width range. In case if there is a chance for collision between insertion part and stator slot edge, it can damage coil, coil insulation and robotic operation. To avoid this, the researcher opted to techniques for the easy operation of the device; rotating the mounting table and guide the end part of the robot with mounted robot guiding sensor. Since the generator mounting table is adjustable, it is very convenient to rotate the stator and position it regarding the robot platform. Also, the sensor system available with robotic arm helps to position the insertion part align precisely.

5.5.2 Dealing with overlapping issue

This is explained with the figure shown below. It is normal that the lower coils from slots 38 to 46 cannot be inserted since the slots are already occupied by the top layers. Therefore, top layers should be removed in order to insert the lower insertion layer. The top layers can be removed by pressing them out from the stator slots. This process can’t be automated and is done by manually. The taken-out coils are bundled together with the help of a rope and tied together. To insert the new lower layers, they are placing on respective slots and needs to press them inside. However, it becomes a challenge for this study. But re-inserting the top coils which has been bundled before, are possible to insert again with the help of robot operation. The figure 5.20 below showing the schematic representation. TL is the top layer and SL is the sublayer.

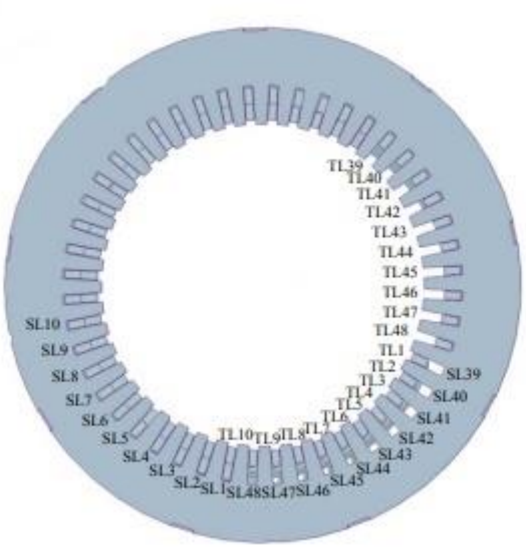


Figure 5.20 Dealing with overlapping issue

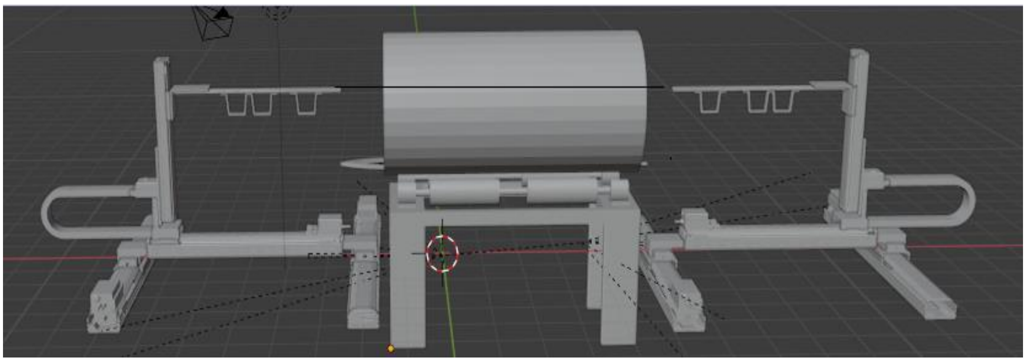


Figure 5.21 Alignment of the job arm

As the above figure 5.15 shows, the job arm of the two robots come in same line at their work point. Figure 5.16 showing the job arm position inside the stator. To reduce the chance for collision between the stator parts, the job arm kept at the centre of the inner stator. For example, if 860 mm inner diameter stator is used, then the zero position of the job arm is 430mm. Sample representation is shown in figure 5.22.

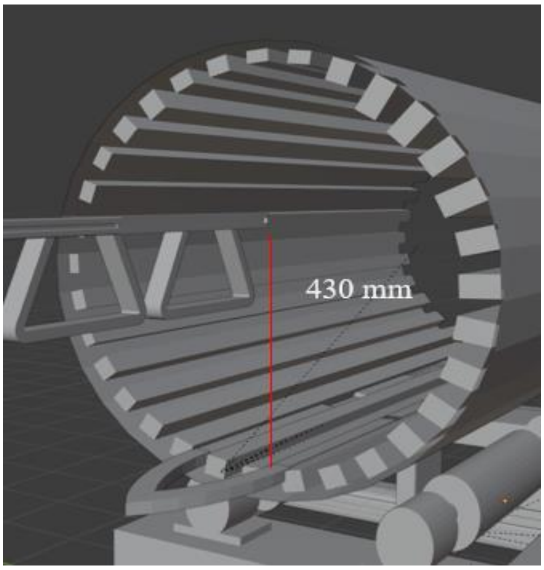


Figure 5.22 Sample representation of position of the job arm inside the stator

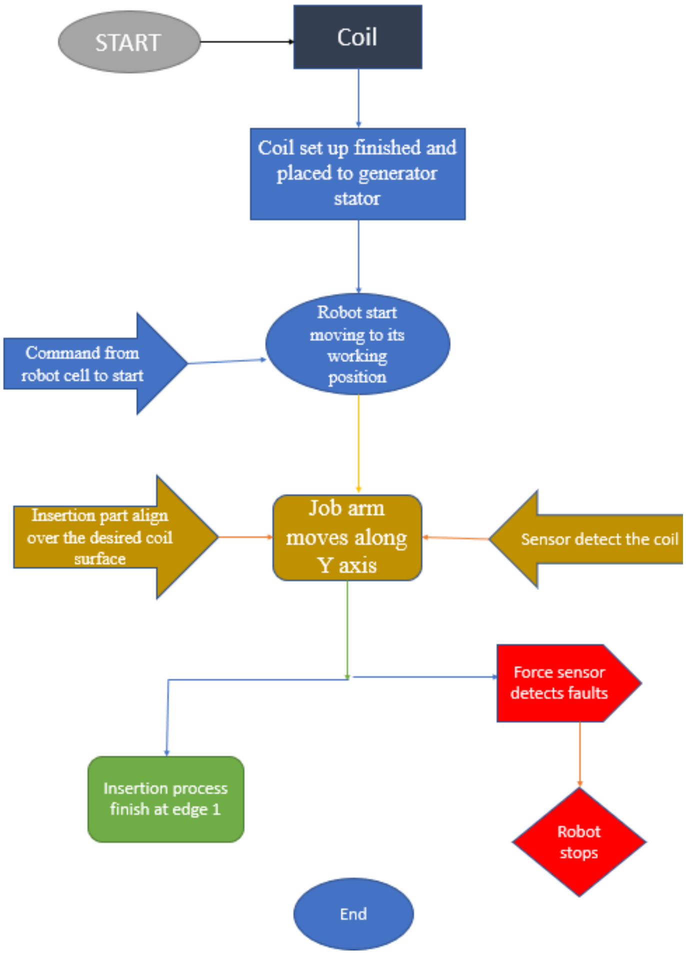


Figure 5.23 Flow chart of the device workflow

5.5.3 Workstation

The workstation consisting the worktable, generator stator, robot system and robot platform. A schematic representation is shown in figure 5.24.

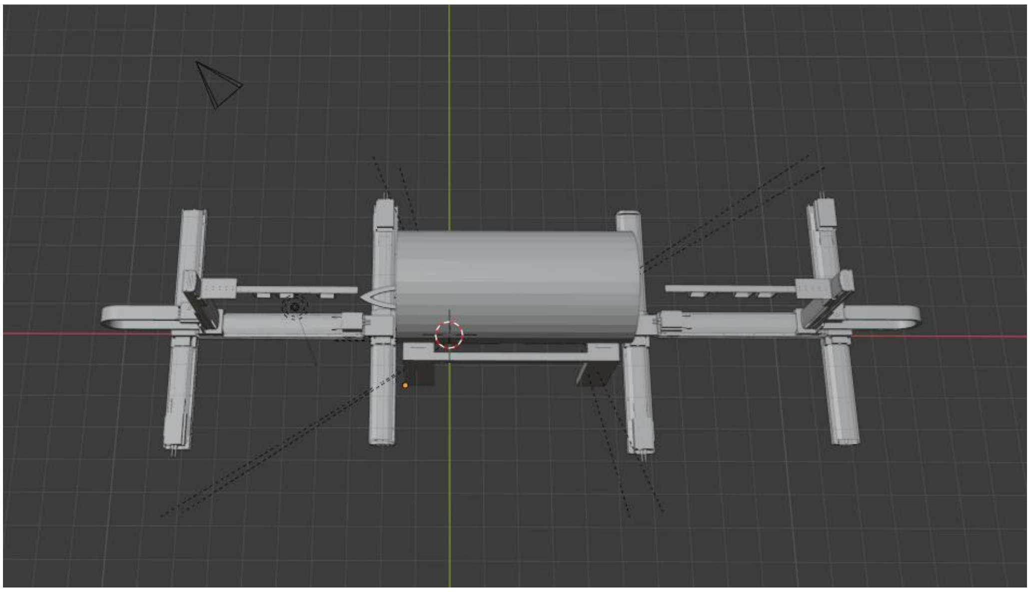


Figure 5.24 Developed workstation

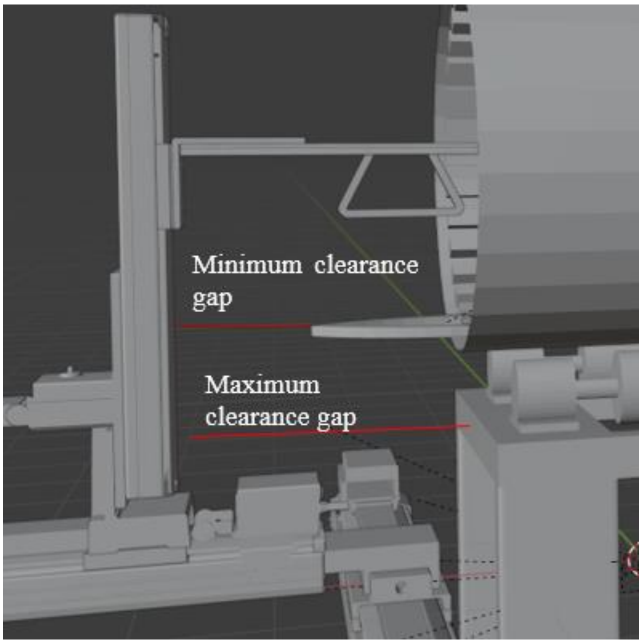


Figure 5.25 clearance gap

The figure above showing the clearance gap of the work system. Clearance gap is defined here as the space available between robot platform and worktable of the generator stator. The researcher defined two clearances as minimum clearance gap and maximum clearance gap. Minimum clearance gap is the distance available between the space of Y axis of the robot and end point of the projected coil tip as shown in red line above figure. Maximum clearance gap is the distance available between the space of Y axis of the robot and table frame. The researcher has taken the clearance gap as follows

minimum clearance gap = 100mm

Maximum clearance gap = 200 mm

The difficulties about this has been explained under challenges.

The figure below shows the robot platform using the Yamaha robotics MF type actuating linear moving platform. They have been chosen 500 mm of stroke length and width is same as the parent robot X axis stroke length 750 mm. The more details about the product can be found from [13].

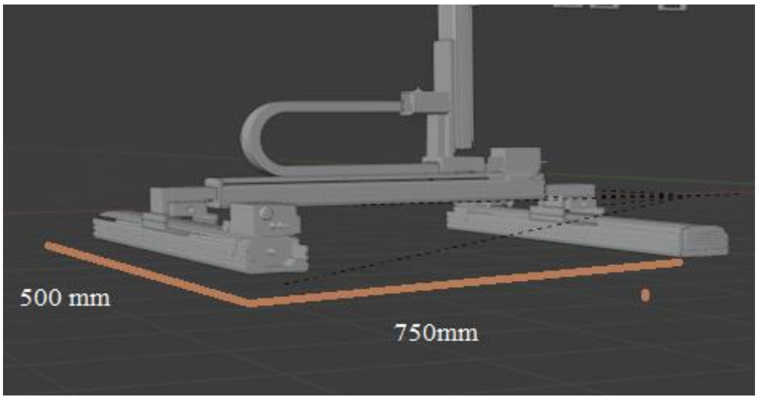


Figure 5.26 Linear type moving platform for parent robot

Figure 5.27 Linear Moving system used for the robot platform [13]

5.5.4 Controller RCX 340

The control model from Yamaha, RCX 340 is used for the controlling of multi axes and 2 robots systems used in the insertion process. This controller model is suitable for controlling the selected parent robot type XY-x model. Multi -systems can be controlled by the one master controller. The algorithm developed for the controller can be also used for the motion functions as well. It means that the robot systems can be controlled by the RCX 340 controller over the specified path with a controlled speed. More details about the controlled system can be found at the [13]. The advantages of the controlling system are given below,

- Controlled and smooth movement over the specified path
- Multi axes and robot systems controlling at the same time
- Multi - options for axis configuration
- High tracking accuracy
- Compact design and good cycle time

Figure 5.28 Yamaha RCX 340 control system [13]

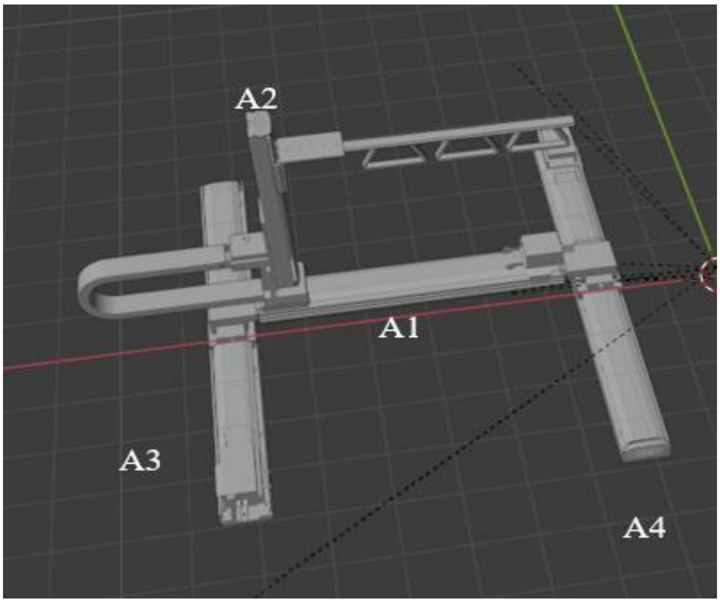


Figure 5.29 Axes moving order mechanism

The above mention figure 5.23 illustrates the mechanism used by the RCX 340 robot controller. A1, A2, A3, and A4 are the axes respectively. A3 and A4 moves with respect to each other. The controller mechanism is as follows,

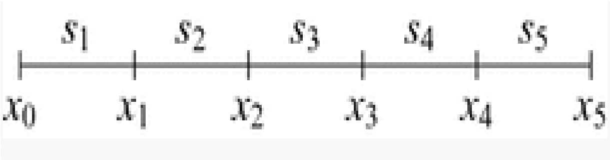
The starting points and stoppage points are specified on the axes A3 and A4. Since they are moving together, it is common for both axes. The stoppage point could be varied for different stators and worktables. Starting point is always 0 mm. After completion of the movement over the A3 and A4 axes, the parent robot starts from the initial point (0 mm over A 1) to the work point. Then the robot controller sends next sequential command for the A2 axis. There also zero point and work point defined to the controlling system.

6 SIMULATION STUDY OF THE DEVICE

6.1 Device motion test and analysis

Consider that the robot is moving with a velocity ‘v’ for a time period of ‘t’ then the distance covered by the robot could be ‘vt’. However, the researcher developed an assembly of cartesian robot system, and it has different movement regarding the tasks. Type of application also affects the robot velocity. As ‘vt’ term is enough to calculate the velocity required for this research work. Also, it is very easy to calculate the velocity over a specified distance.

In order to calculate the acceleration, need to take in account velocity change per time. The acceleration needs to find for X axis movement from Zero position to the work point. Zero-point id defined as the initial state of the parent robot on x axis and work point is the final or stationary point where the parent robot stops and run the command for other desired tasks. The length of the X axis is 750 mm. Since the robot has no stoppage before the work point, the acceleration is same throughout the motion. Even though, a moment before the stoppage the robot decelerate itself for the stopping. It means at some point velocity and acceleration changes. To find out that the researcher has divided the entire length into segments to get the clear idea, as shown below.



Therefore, each segment is 150mm. From here, the researcher has recorded the simulation readings for each segment. Then, it is possible to calculate the velocity and then, acceleration. ‘S’ is the distance between each segment and ‘x’ is the segment number. The length of the segment is given by

$$\Delta si = xi+1 - xi \quad (6.23)$$

The time taken to cross each segment is given by

$$\Delta ti = ti+1 - ti \quad (6.24)$$

The velocity at each segment vi is given by,

$$vi = \frac{\Delta si}{\Delta ti} \tag{6.25}$$

6.1.1 Displacement test

The displacement of the parent robot over X- axis has been determined by the series of simulation tests at different values. The testing values are 80mm/s, 90mm/s and 100mm/s. The simulation test results are given below and finished in Blender simulation environment.

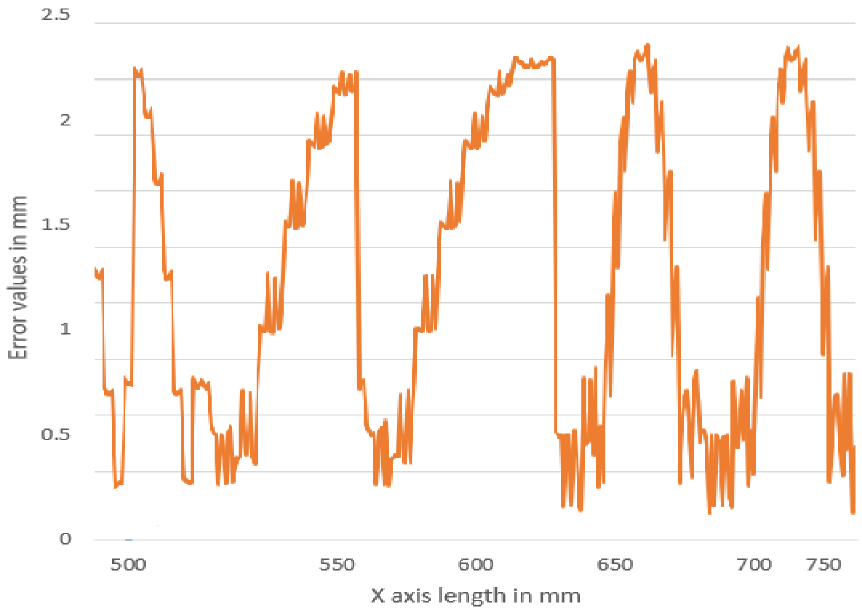


Figure 6.1 Disturbance at 100mm/s

The above graph represents the test simulation carried out in 100mm/s displacement for the parent robot. Those disturbance could be called as 'vibration', or 'instability' of parent robot. More specifically instability of Y- axis along x- axis motion. It happens when the robot start displacing and to stop, it has to decelerate after 500mm to stop in the range of 700-750mm of X- axis. Therefore, from acceleration to sudden deceleration cause this kind of vibration or instability to the Y axis. For a robot, perfect velocity is much needed to ensure it's reliability and effectiveness to the work task. For a X-Y type pole structure, this kind of disturbance occurs as the velocity increases. Therefore, the test has been conducted for the next value 90mm/s.

The below graph represents the test result of 90mm/s displacement. As it indicates, the disturbance due to displacement is better in this case. Although, the test conducted on 80mm/s as well.

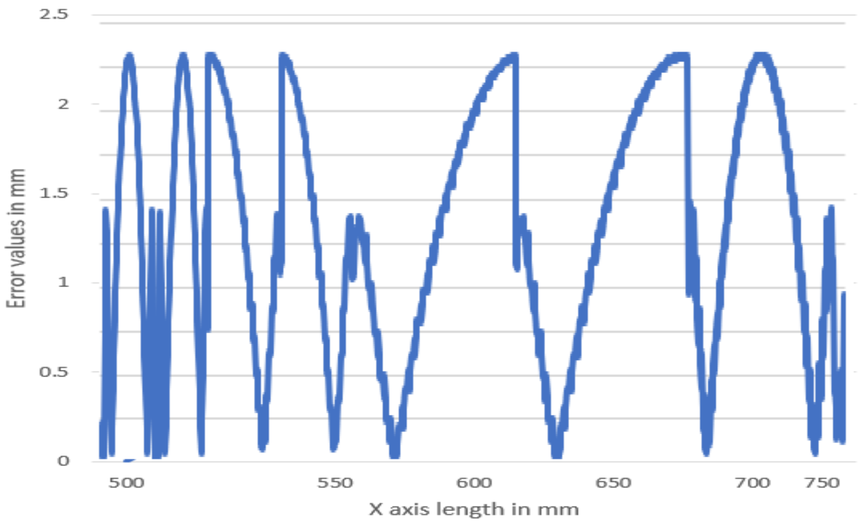


Figure 6.2 Disturbance at 90mm/s

The disturbance on a X-Y type pole structure happens not only because of the high displacement but also as it carries insertion tool and frame on it's job arm (Y axis). Here, insertion part is necessary and not possible to reduce the weight as all the required components should there for the work task. But, the researcher succeeded in designing the components so as to reduce the weight.

The test for 80mm/s has conducted and result is given below. As it shows, the disturbance is very low and much better for this range.

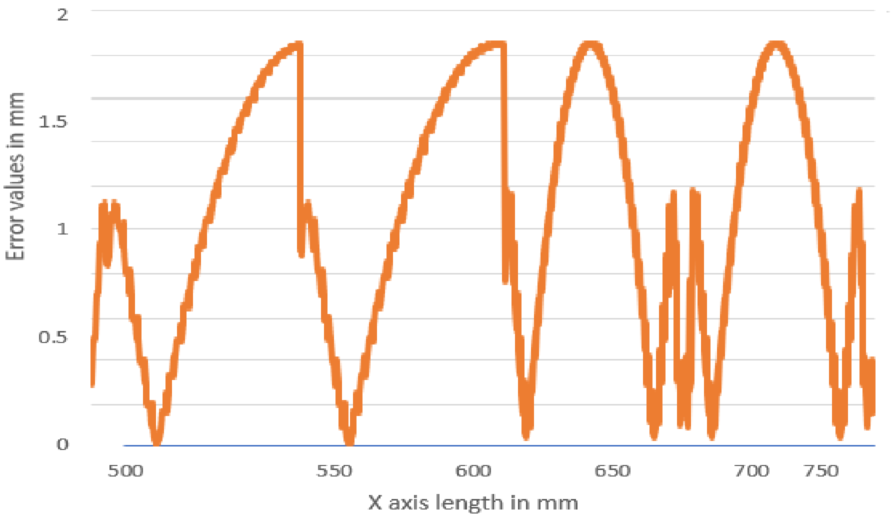


Figure 6.3 Disturbance at 80mm/s

From all of the above-mentioned results, it is clear that the disturbance of Y axis system over X – axis is less and better in test conditions under 80mm/s. Therefore, parent robot displacement over X -axis is taken and decided to be 80mm/s.

6.2 Axis analysis

To determine the average speed of the parent robot and insertion arm, a series of robot simulation has been conducted. The results and charts has been evaluated and the value is determined based on the simulation results. The simulation has been done in Blender software which is a high-end platform. As the researcher discussed earlier in dynamics, it is not good to find the average speed by putting a value on those equations and concluding them. Therefore, the simulation results are carried out for different specific values and results are concluded as in coming sections. The detailed analysis has been given in following descriptions.

6.2.1 X- axis analysis

The distance travelled by the Y axis over the X axis has been given below. The velocity is 80mm/second.

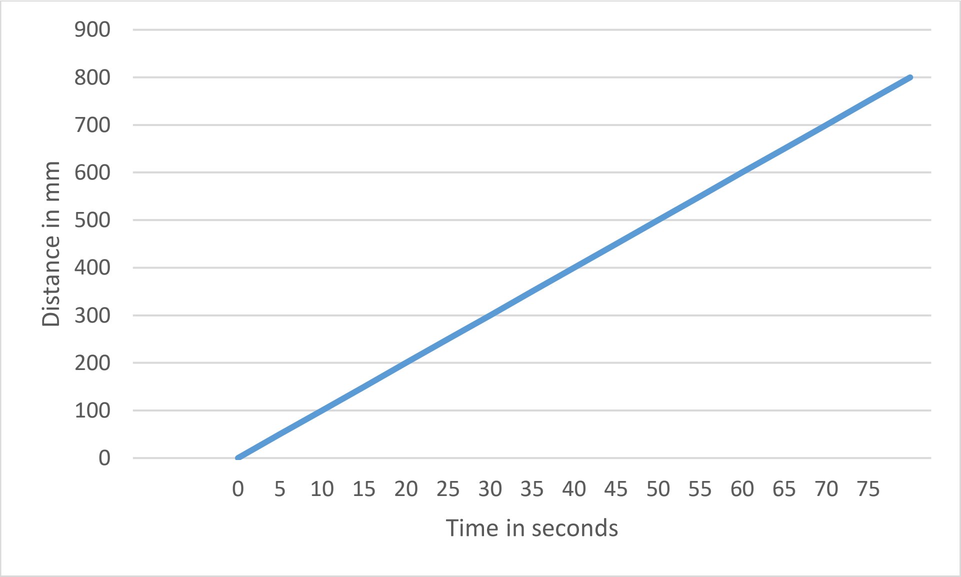


Figure 6.4 X axis Distance - time graph

The figure 6.7 below indicates the velocity of the robot over X axis with respect to distance. It shows that at some point of the time, the velocity start decreasing. This means, after 500 mm, the robot start decelerating itself to stop at the specific position.

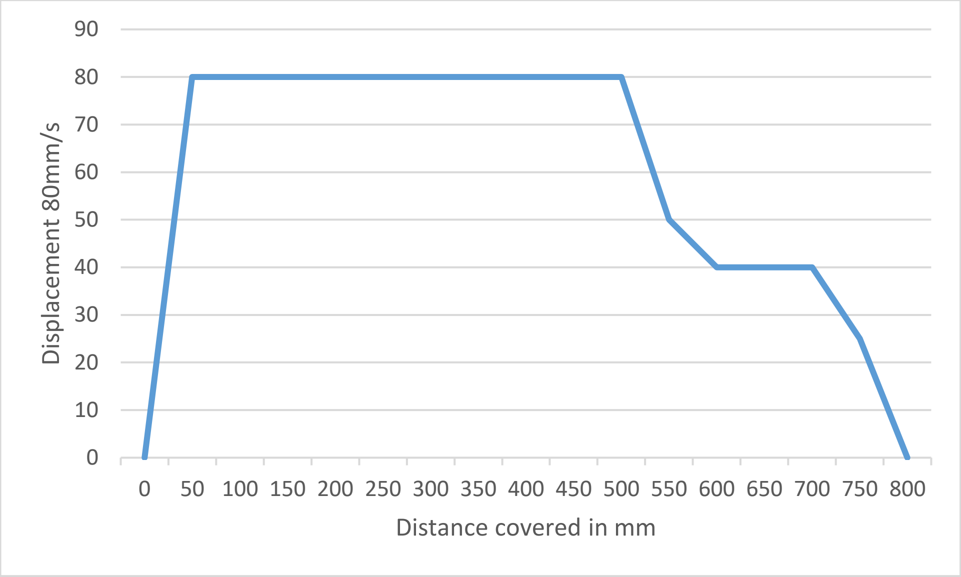


Figure 6.5 Displacement - distance covered

6.2.2 Y – axis analysis

This graph below showing the position of the work arm over Y axis.

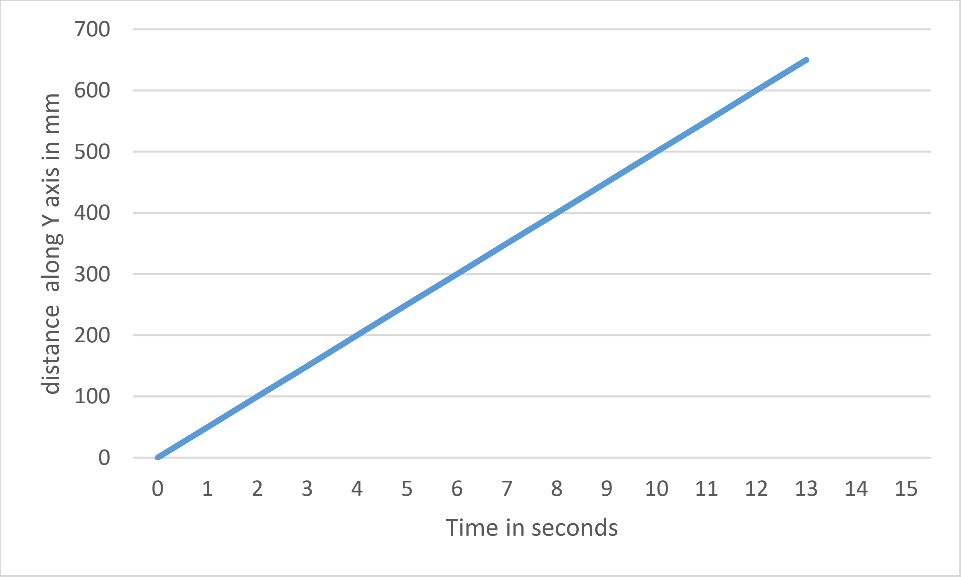


Figure 6.6 Y-axis, Distance versus time graph

When the insertion process starts, the acceleration is not relevant.

In order to reduce the work waiting time, the insertion part is placed near the work object and called as working position. Therefore, the robot moves towards the direction of the working position of the insertion part and stops and position at that point. Once the coil has been placed manually inside the generator stator, the robot starts moving and position itself with the help of the robot guidance system. The very important factor to be find is the average moving speed of the insertion part and parent robot which can be calculated by following the above-mentioned dynamic theories.

6.3 Simulation results and analysis

6.3.1 Job arm simulation

The job arm stroke length is 650mm throughout the Y-axis of the parent robot (Black mark line in figure 6.10). And it's zero position is defined at 650mm. Zero position is the point where the insertion frame held stationary at the initial stage of the task. For the insertion process, the insertion frame starts moving from zero point(650mm) towards the down of the Y axis.

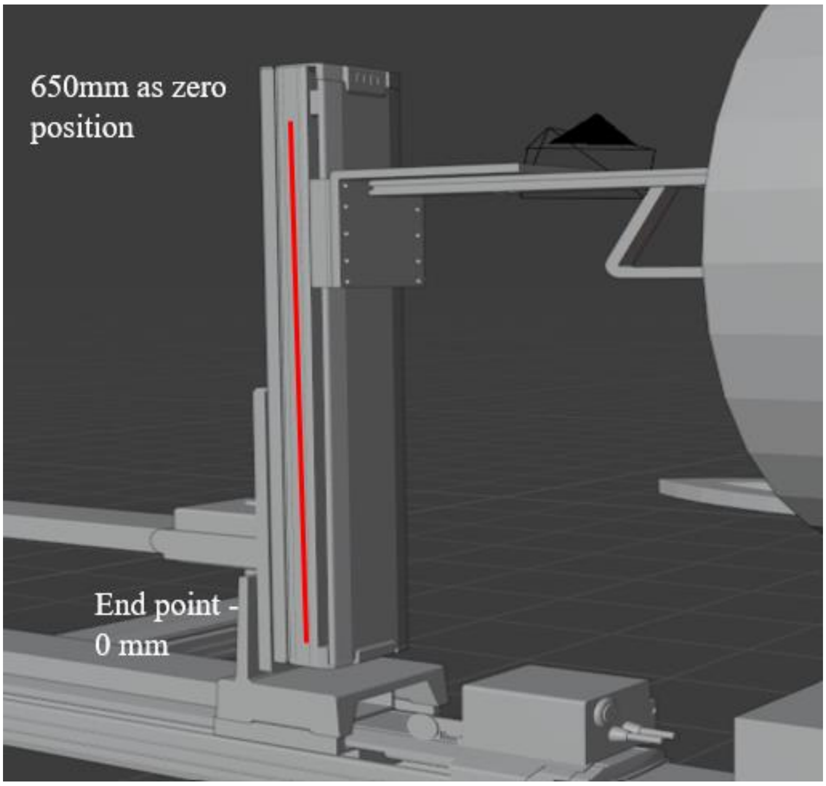


Figure 6.7 Job arm stroke length

The lowest position job arm reaches the 150mm of the Y axis stroke length. The simulation of the job arm is conducted in between 650mm to 150mm. The job arm movement along Y- axis graph is shown in figure 6.8.

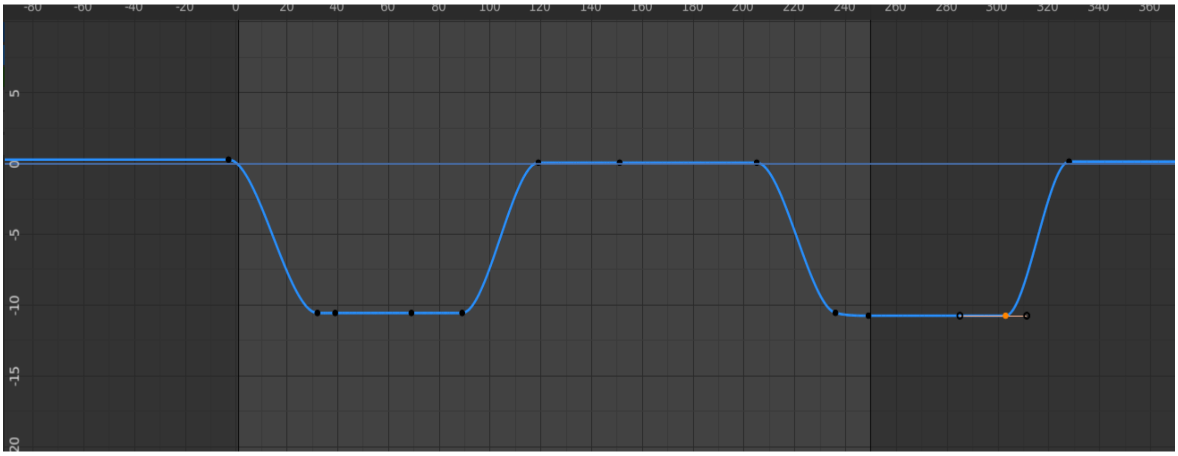
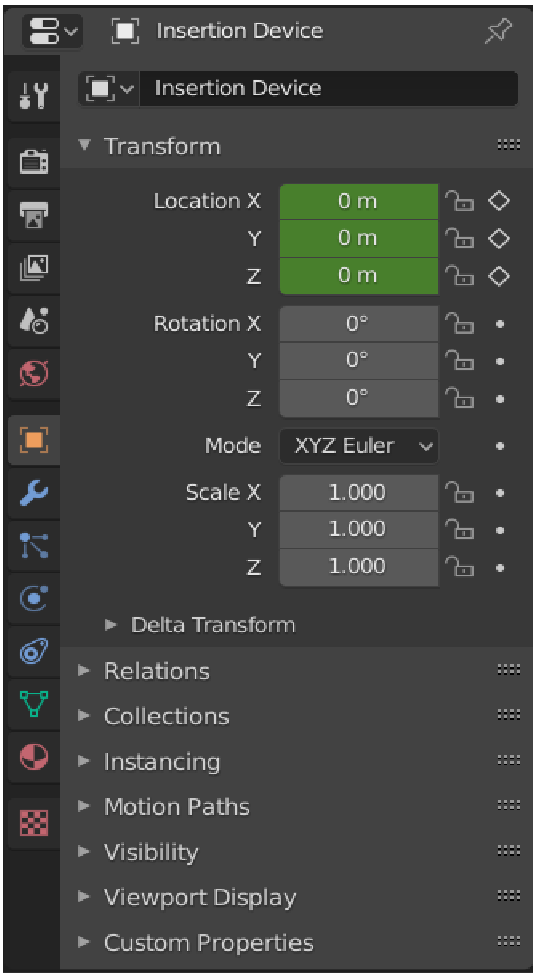


Figure 6.8 simulation path of the insertion - job arm. Developed in Blender simulation software



Insertion Device

Insertion Device

Transform

Location X 0 m
Y 0 m
Z 0 m

Rotation X 0°
Y 0°
Z 0°

Mode XYZ Euler

Scale X 1.000
Y 1.000
Z 1.000

Figure 6.9 Input panel

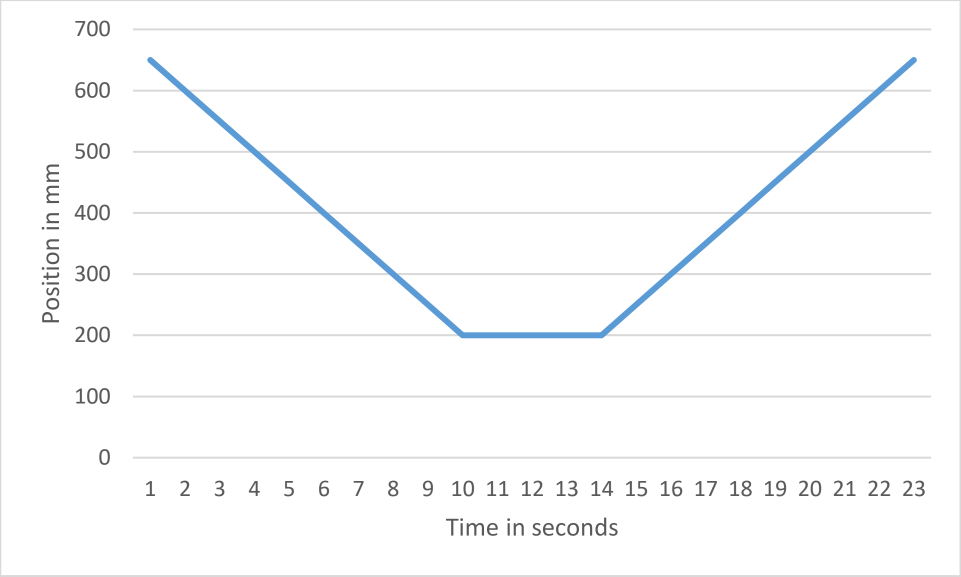


Figure 6.10 position vs time graph of the job arm during insertion

The above graph represents the position of the job arm with respect to time. it means that, the first slope stands for the job arm displacement from it's zero position to work point at 200mm. after that job arm is stationary for insertion process. And then after 5 seconds, job arm again moves upwards to its zero position.

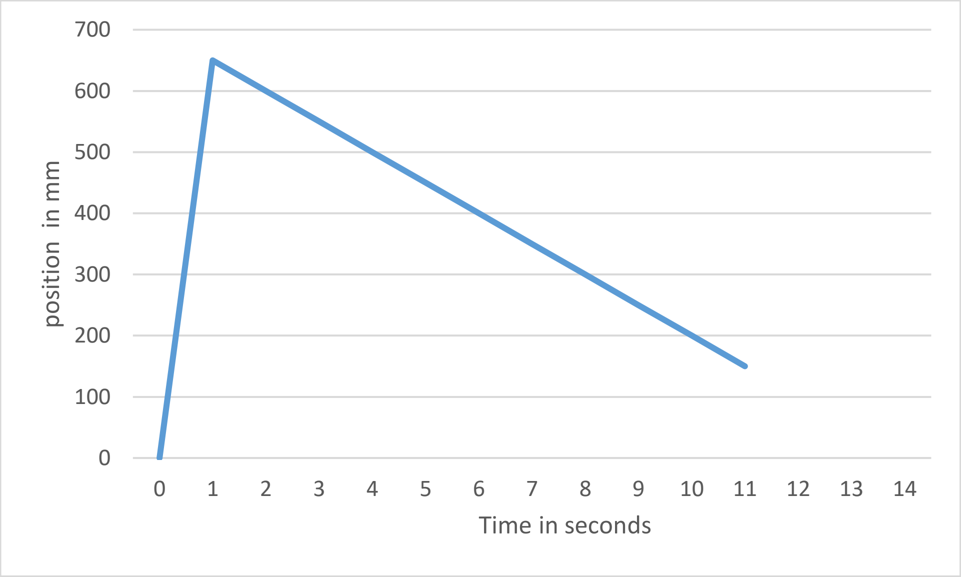


Figure 6.11 Position - time graph of the job arm

The above graph shows the position of the job arm with respect to time only for free y axis movement.

6.3.2 Insertion process analysis

The insertion process starts once the insertion part comes and aligned over the coil surface. The below figure 6.12 shows force versus displacement graph. The displacement corresponds to the coil displacement. More specifically, the coil moved inside the slot. The slot depth taken for the simulation condition is 50mm.

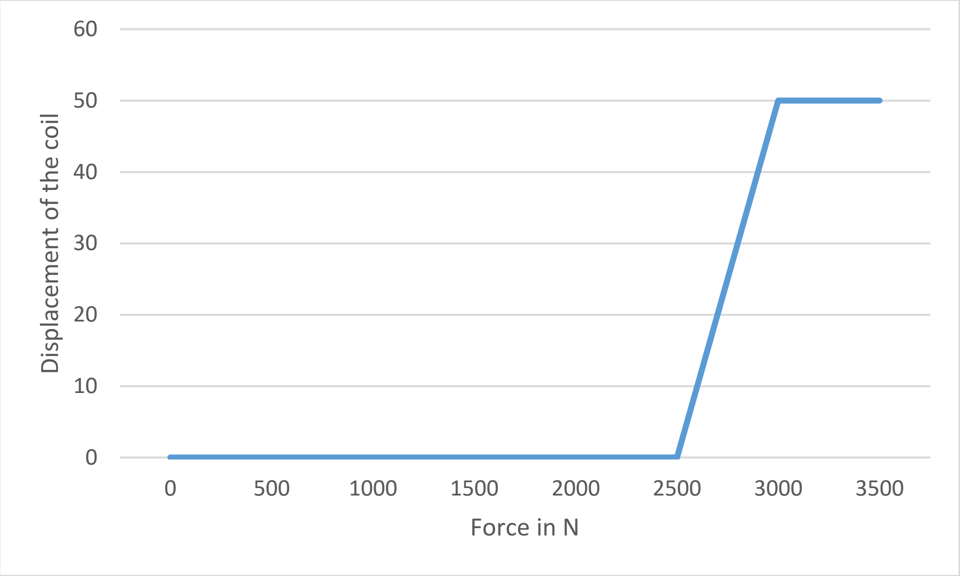


Figure 6.12 Coil displacement in slot - Force graph

The graph below shows the relation between distance travelled by the robotic arm to the displacement of the coil to the slots. This graph shows the data about the starting and end point of the coil insertion with respect to job arm movement. More specifically, it gives exact point where insertion starts and ends with respect to Y – axis.

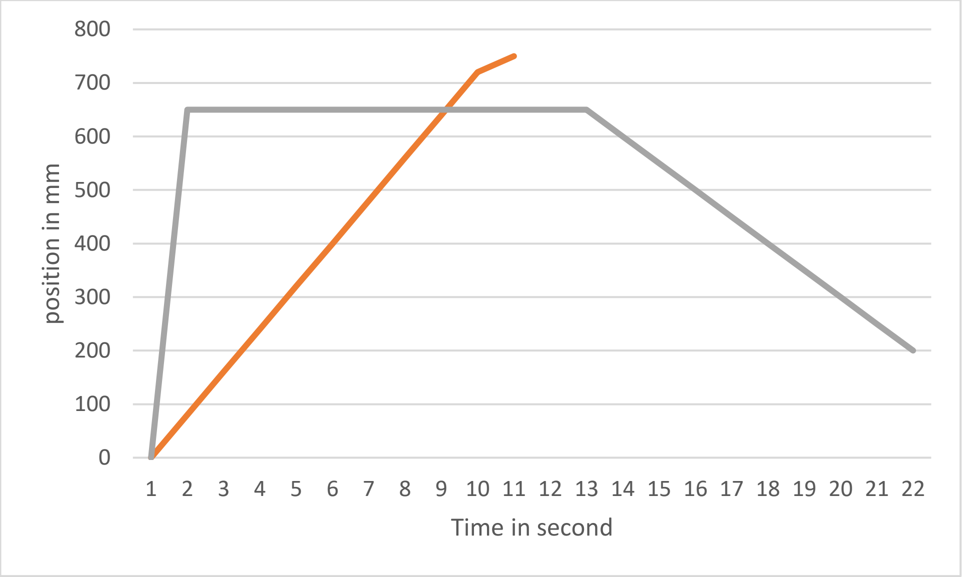


Figure 6.13 Relative graph between Job arm and insertion part position with time

The above graph shows the position of the job arm and insertion part with respect to time. Pink line indicates the position of the job arm on the X- axis. Grey line indicates the position of the insertion part on Y axis. As it shows, the job arm start moving from zero position (650mm) to 200 mm lowest on the Y axis.

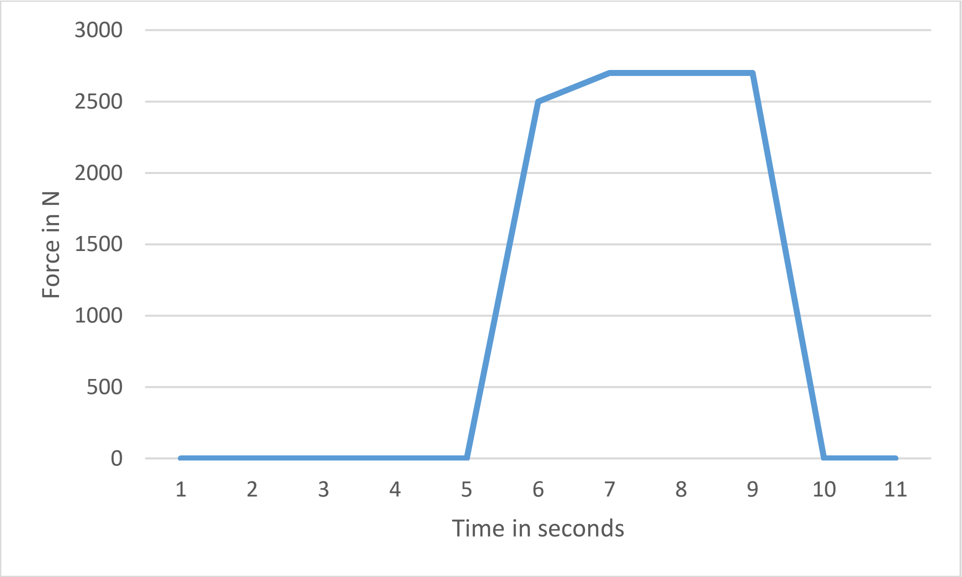


Figure 6.14 Force vs time graph

The above graph shows the force exerted with respect to time. The force start exerting at 5th second. This test condition is taken after the insertion part comes at insertion point. It means, about at 200mm on Y axis. After positioning at that point, the force start exerting using the motor system on the job arm frame structure. The insertion is finished within seconds and the force becomes zero after that. The job arm moves to its zero position again and wait for the next round of the insertion work task. This is more clearly resulted in following figure 6.15.

The graph below shows the relative result of the job arm position and insertion force with respect to time.

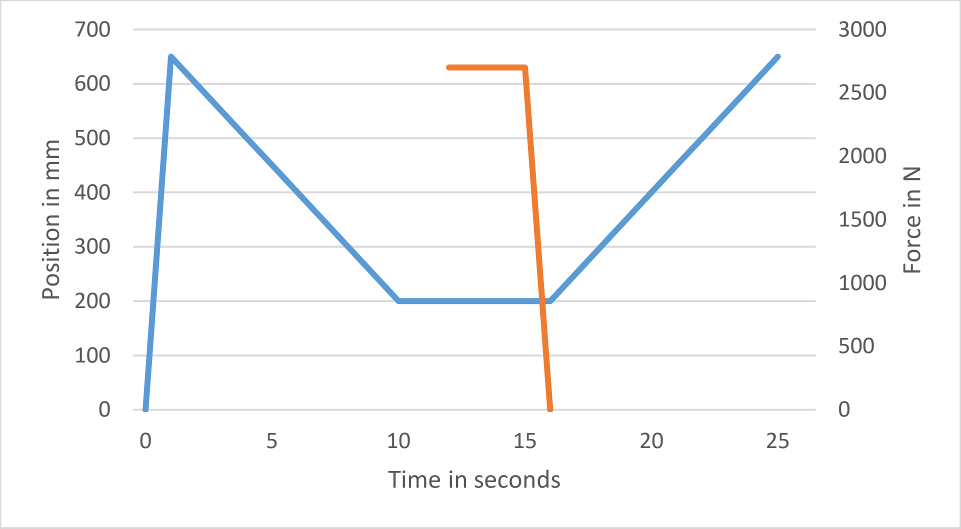


Figure 6.15 Position - Force vs time graph

6.4 Ensuring the safety

Safety is a big factor when come to the robot operation. It ensures the complete safety of the workers, equipment’s, and entire industrial environment. The used robot model is a model which offers high level safety system to its working surroundings. In this research work, the workers and robot have to work closely and thus it becomes challenging to create the safe work environment. As the robot itself comes with a object detecting system both for its axis motion and coil detection purposes. The object detection system and technology [12] [13] available from the Yamaha manufacturer promises the highly sophisticated level of technical specification for object tracking for it's axis motion. The robot vision processing system is given below in figure 6.16.

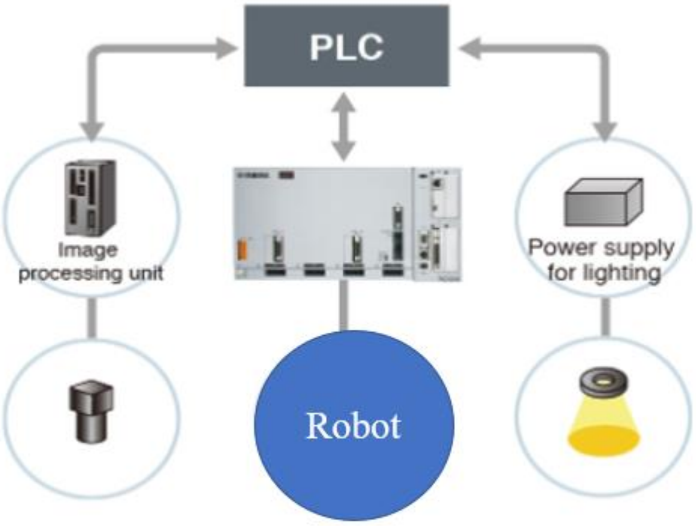


Figure 6.16 Vision set up of the robot system.

The robot is controlled by the RCX 340 robot controlling system where the entire insertion process is commanding from. In order to avoid the over force exertion, the maximum force limit 2850N is set on the controlling panel of the robot. This input data controls the thrust produced by the linear motor present Y axis (which pushes down the worm arm). whene ever there is an obstruction or obstacles happens during the pushing down of the coil, the process needs to be stopped. If there is no controlling of the force exertion, the robot will continue its work and may break and coil and damage the entire product. To avoid this scenario in future, the maximum force value is set us 2850N (depends on generator size as force value varies for different stator variants).

Two robots are used for this research work, to control the two robots work simultaneously, RCX 340 robot system helps. The workstation is isolated from the other free space inside the industry room by using fences. It is not completely closed type but it is closed to the faces or regions where there would be a chance for close contact with the robot’s external space. More clearly, in industry workers are moving around and other functions are taking place at different workstations it is necessary to differentiate those space from the robot working place. This will help to ensure the safe working of the robot and other workers as well inside the factory.

And this robot is able to stop simply and emergency stop available in the Yamaha software environment. If something bad happens or danger happens, then it is also possible to stop the robot using the software controlling panel. Of course, a emergency stop button is also available for the robot system other than the software mode.

6.5 Challenges

6.5.1 Chance for collision with coil

The robot arm will move regarding the sensor reading. For example, the sensor fixed at the dead end of the robot tool would adjust to sense the stator slot end or stator frame ending. Then the robot moves up to the end towards that direction. The sensor from robotic arm end will sense the entry side end of the stator. Also, if the insertion part projecting outside of the system, then it may come and press on the projecting end of the coil tip. Therefore, positioning inside the stator is still a challenge for the research. This is shown in figure 7.1.

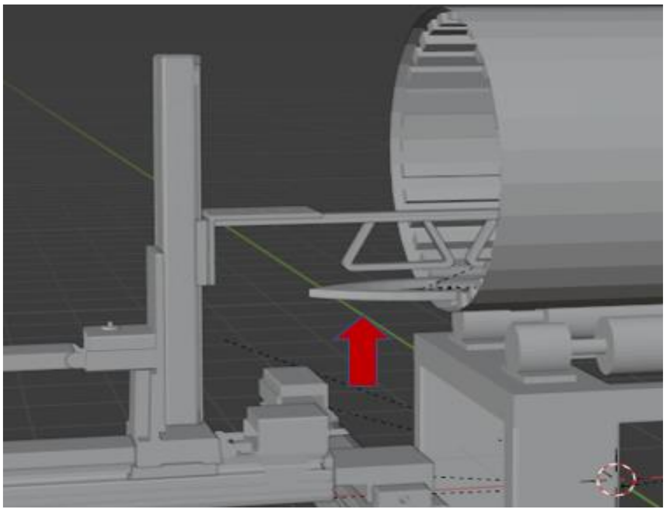


Figure 6.17 Chance for collision and breaking of the coil ending.

6.5.2 Adjustable insertion part

The length of the insertion part is not possible to changeable at the moment. Because, not using same length of robotic tool for all stator length. More clearly, choosing 700mm tool for 1000mm stator length, then we cannot use it for 500mm stator length since the rest 300mm project towards outside from the stator. Therefore, the author decoded to focus on developing a robotic tool for certain range of stator length in between 800mm to 1200mm.

Another issue arising due to the adjustable insertion part is to the sensor. The sensor has been mounted regarding the length of the robotic tool frame and insertion part. So, if replacing with an adjustable insertion part, the sensor should also be adjustable kind of mounting on frame. This further arise the problem of modifying the robot tool frame and thus finding suitable solution or mechanism for adjusting the sensor.

6.5.3 Movement of the robot

The movement of the robot also should be taken in account. Since it has to reach the opposite end of the stator frame, there should be an adjustable kind of movement from the robot is necessary. As per current progress, the scholar decided to use a linear movement system mounted over a platform or table. Even though it could provide robotic movement, it arises the challenge to modify the workstation area. It means that, adding an extra working tool or system would reduce the current work area which will force to modify the entire workflow and tools at present

6.5.4 Overlapping issue

After the first winding process of the coils, the second set of winding is followed. For this operation, the top layers formed by the primary winding needs to be removed in order to insert the lower layer coils in second round insertion. For this, the coils need to be tied together using a rope. This becomes challenging for the insertion process.

7 CONCLUSION

The major motivation behind the research work to develop the robotic tool is to reduce the human effort during the hammering process for coil insertion. This research is the first and beginning in this field. When it comes to smaller diameter generator stators, it is very difficult to do the hammering process since the room space become less after first round of winding. The author has visited and witnessed the industry and work during the process. From this scenario, got the motivation to establish a system for insertion process. The coil type used for the generator is form coils. They have a rectangular shaped surface which cannot be automatically wound as copper coils. Therefore, form coils are inserting by human hammering process. This could result in damaging the coil insulation and quality as well as human injuries. Therefore, this paper researching the possibilities of solutions for automating the human hammering process. This paper found and developed multiple designs and chosen a better design. As it is clear from the research paper, study has been gone through all possible ways including smaller to larger stators, different stages of tool development, simulation of the tool and FEA analysis. The motto is to design a tool that fit to current workstation and workflow. But this is not the final or last result. The scholar has finished all the possible outcomes and tried of best. As it is a first kind of research done in this area, there are still a wide opportunity to study and upgrading the tool.

As long as the research deals, the study is successful in establishing a model for the winding operation. The FEA method includes the stress, strain, analysis over the specified and selected parts and materials.

7.1 Future works

The main agenda for the future work includes the development of simplified working robotic tool which can be applied to both smaller and larger stator windings. Although this paper has finished major findings and studies about the topic which is more relevant to future development. In fact, no design is perfect and can be modified. The areas which has to be improved are explained well in this paper. Working on those could give a better output than what we have now. There should be a detailed study about the minimalization of robotic tool frame which can deliver all winding process. As it takes time for detailed study. During this research, author has familiarized with different levels of tools and techniques for design. With all these findings, the robotic tool can be upgraded into an efficient and innovative device in future.

8 SUMMARY

8.1 English

The purpose of this research work is to develop a device for automating the hammering process during coil insertion at ABB M&G factory, Juri, Estonia. This research is the very first level of a work for automating the human work in the industry. The workflow in the factory is labour intensive and automating that is not an easy process. The automated form coil winding is not as copper coil winding. There is no existing solution in the industry level. The study has been carried out mainly in three steps: industrial work study, design development, simulation analysis. The industrial work study deals with, learning and adapting with daily workflow in factory environment. It includes each stages of winding process from initial level to final level. By analysing this, the researcher was able to understand the challenges and conditions taken in account for device development. The robot is a replacement for human task. Therefore, a robot should be capable to do all of the human tasks.

Design development has been carried out in four stages of development. During all of them, the researcher has seen enormous range of design aspects. Learned and developed different tools and skills during this study. Selecting the material for robot tool frame was based on industrial study. Aluminium 6061 and steel metal alloys are the majorly used materials for the design of device parts. Since the coil type is 'form coil', there is no technology or method practically proven in the industry level on this topic. As it is first kind of topic in industry, this paper had proved and resulted many good results about automating the hammering process for coil insertion. The main agenda is to reduce hammering process to avoid damage to coils and reduce human accident injuries. In that sense this study is successful.

Although the main goal was automating the hammering insertion of the coil into stator slots. As the paper stated in result section, got so many good results and challenges during the simulation and analysis of the developed design model. The scholar focused on insertion process only since picking and insertion not possible at the same time. Not only that, but also human presence required in certain scenarios such as worktable operation. This research is first in this industry and has a major role in future upgradation. Based on this study, more efficient and sophisticated robot or device could be developed and implemented in future.

8.2 KOKKUVÕTE

Selle uurimistöö eesmärk oli töötada välja mähiste staatorisse sisestamise seade ABB M&G tehases Jüris, Eestis. See uurimus on tööstuse automatiseerimise kõige esimene etapp. Tehase töövoog on töömahukas ja selle automatiseerimine ei ole lihtne protsess. Uuring on läbi viidud peamiselt kolmes etapis: tööstustöö uuring, konstruktsiooni arendus, simulatsioonianalüüs. Tööstustöö uuring käsitleb õppimist ja kohanemist igapäevase töövooga tehasekeskkonnas. See hõlmab kõiki kerimisprotsessi etappe alates algtasemest, kuni lõpptasemeni. Seda analüüsides suutis autor mõista väljakutseid ja tingimusi, mida seadme arendamisel arvesse võeti. Robot on inimese töö asendaja. Seetõttu peaks robot olema võimeline täitma kõiki inimese ülesandeid.

Konstruktsiooni arendamine on läbi viidud neljas arendusetapis. Kõigi nende jooksul on autor näinud tohutult erinevaid kujundusaspekte. Uurimise käigus õppis ja arendas erinevaid tööriistu ja oskusi. Roboti tööriista raami materjali valimine põhines tööstuslikul uuringul. Samuti on tööstuses saadaval lai valik haaratsisorte. Sobiva valimine pole lihtne ülesanne, kuna see töö on väga erinev tavapärasest valimise protsessist. Töötava osa väljatöötamiseks on läbi viidud üksikasjalik analüüs, mille jooksul on esinenud tõrkeid ja nendest tulenevaid probleeme. See sundis nendes oludes seadme konstruktsiooni veelgi parandama.

Peamine eesmärk oli sisestamisprotsessi vasardamisprotsessi automatiseerimine. Aga nagu lõputöö tulemuste osas esitati, esines väljatöötatud konstruktsiooni simulatsiooni ja analüüsi käigus palju ebaõnnestumisi ja väljakutseid. Seega autor keskendus ainult vasardamisprotsessile, sest mähiste transporteerimine ja sisestamine pole samaaegselt võimalik. Lisaks sellele ka inimese kohalolek on vajalik teatud olukordades, nagu näiteks anduri paigaldamine ja töölaua töö. See uurimus on valdkonnas esmakordne ja sellel on tulevikus suur roll. Selle uuringu põhjal saaks tulevikus välja töötada ja rakendada tõhusamat ja keerukamat robotit või seadet.

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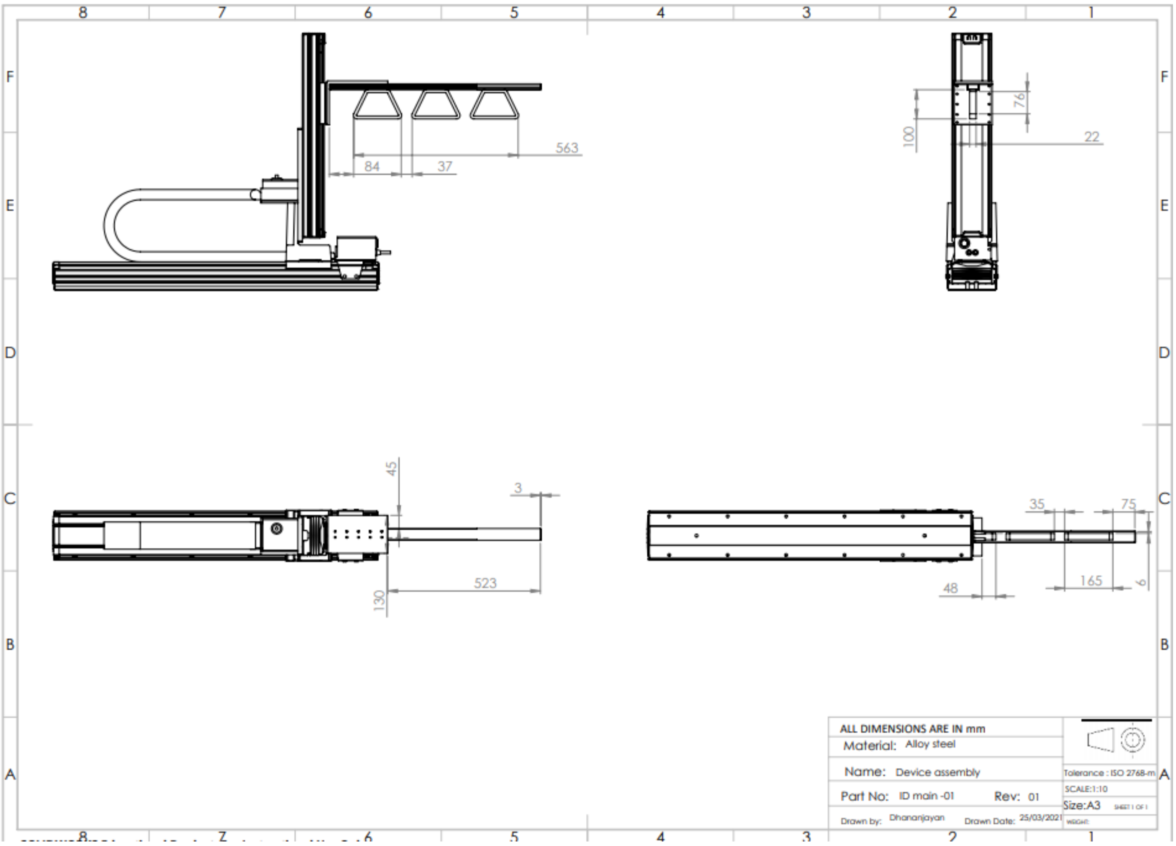
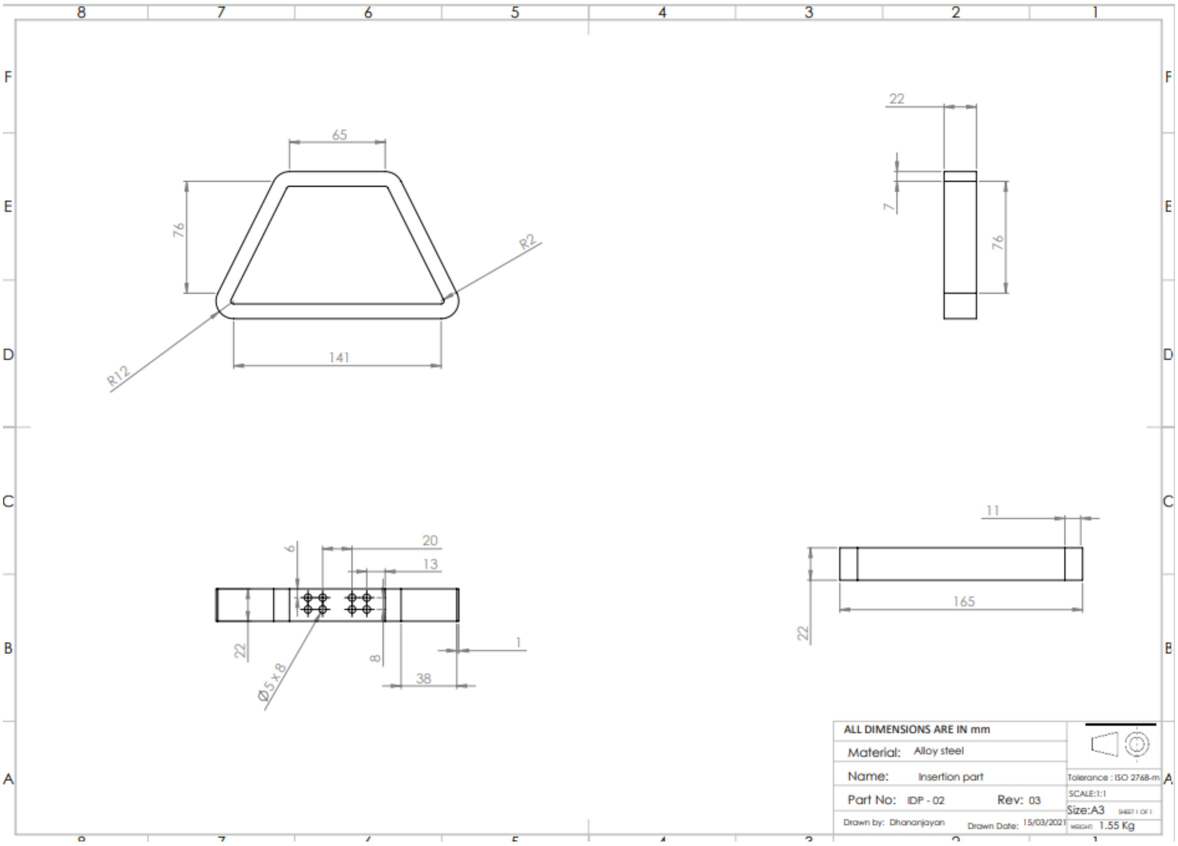
APPENDIX 1

Parent robot assembly



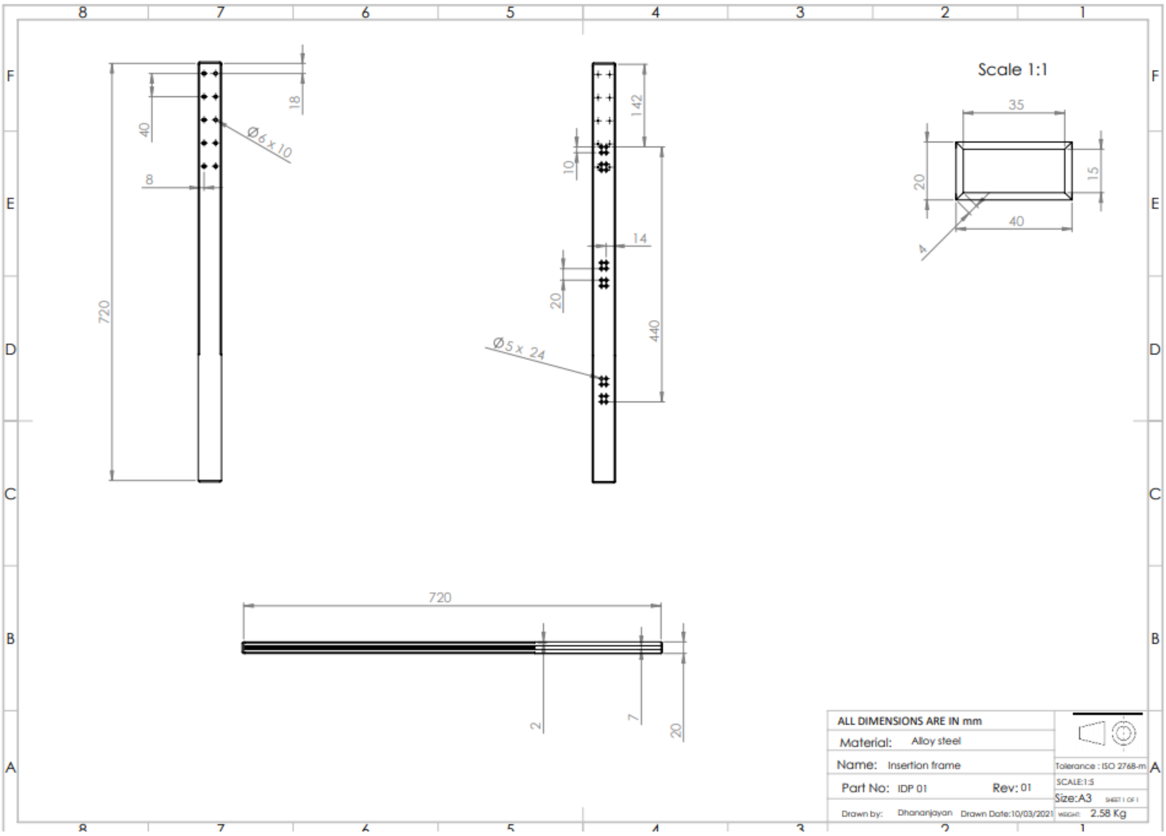
APPENDIX 2

Insertion part



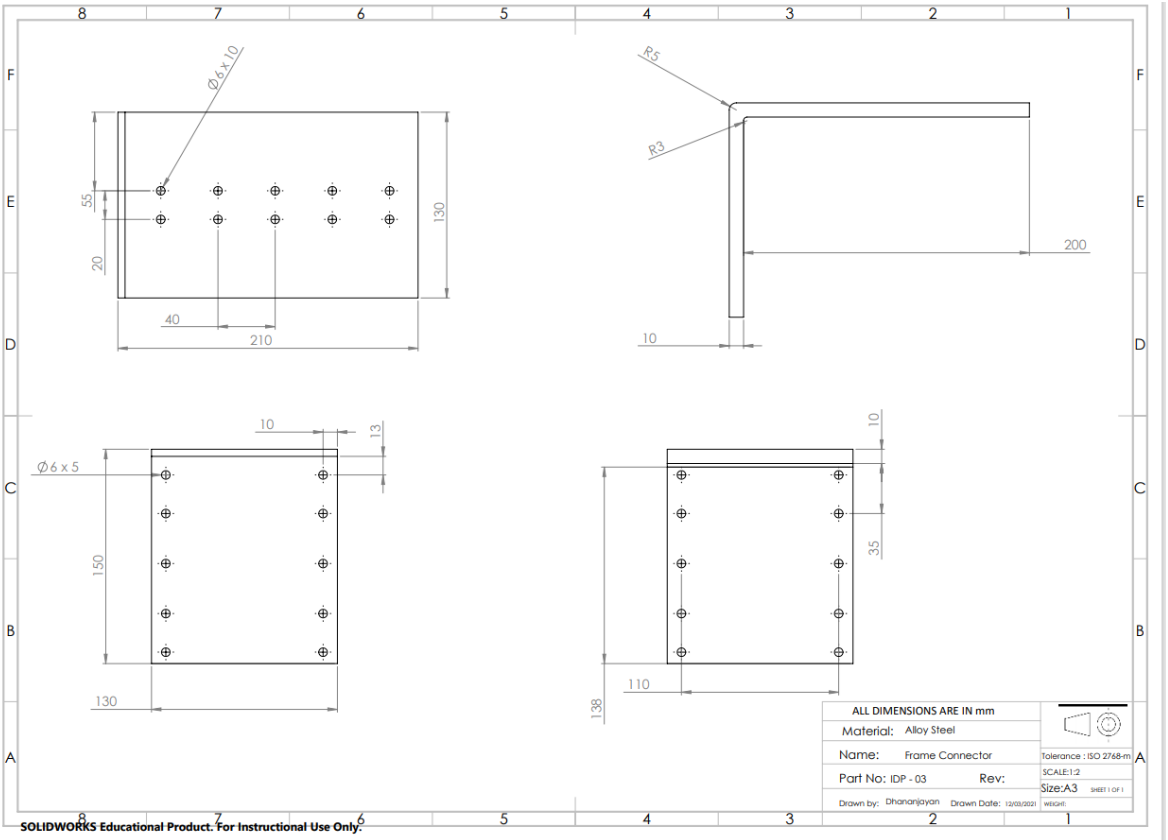
APPENDIX 3

Job arm frame



APPENDIX 4

Connector



APPENDIX 5

Stator design data