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Design of a Three Axis Robotic System and its Implementation as a 3d Printer

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***Abstract* - This paper gives a complete insight on the systematic procedure required to be followed for design of a three axis robotic system and its implementation as a 3D printer. The mechanical structure of the system is designed based on dimensional and load carrying requirements. The system is equipped with a suitable material extrusion system along with a control system that allows its use as a 3D printer based on the principle of fused deposition modelling.**

Key words: Design, Fused deposition modelling, 3D Printer, ANSYS.

Notations:

F_a = Allowable tensile stress
UTS = Ultimate tensile stress of the material under consideration.
Fos = Factor of safety.
R_E = Force exerted on the structure by the extruder.
t_R = Required thickness of the Center carriage
M = Bending Moment
L = Length of the Center Carriage
B = Breadth of the Center Carriage
z = Section modulus of the beam
L_G = Length of the girder
R_D = Dead weight of the center carriage and the bearings
R_G = Net load acting on the girders
d_G = Required diameter of girder rods.
μ = Co-efficient of friction.
I_G = Moment of Inertia of the rod
R_F = Frictional resistance
Rx = Maximum load acting on each of the end carriages due to X axis
R_M = Total load acting on end carriage 1
R_B = Maximum load acting on each rod of bridge
L_B = Length of the bridge rods
I_B = Moment of inertia of bridge rod.
d_B = Required diameter of bridge rod.
L_z =Length of the base plate
B_z= Breadth of the base plate
T= Required thickness of the plate
F_z = Total Load in z direction
R_Y =Total frictional resistance in in Y direction.
D_z = Diameter of the guide rods
K_b = Combined Shock and fatigue factor
τ = Design shear stress
α = Column action factor
F =Load to be raised or lowered by lead screw
d_l = Mean diameter of the lead screw
l = lead (Axial advance for one complete revolution of the screw)
R_z = Frictional resistance between nut and lead screw
N_z = Load Normal to the vertical rod axis

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I. INTRODUCTION

Additive Manufacturing is one of the latest trends adopted by a large number of industries in recent times. Additive manufacturing facilitates rapid production of prototypes in a cost effective manner and hence is used by the industries to create a scaled down model of the actual product. The scaled down model gives a brief visual idea of the look and feel of the actual product before the actual production.

3D printing by Fused Deposition Modelling is an additive manufacturing technology that uses a Three-Axis robotic system to produce a 3D model from a digital file. The object is printed layer by layer by an extruder that deposits thin (thickness in microns) layers of material. The materials commonly used (Polylactic Acid-PLA and Acrylonitrile Butadiene Styrene-ABS) are such that they quickly solidify at room temperature. As a result the object continues to maintain the solid shape even as layers of liquid material keep on getting deposited on it continuously. Since the objects are printed layer by layer, a wide variety of objects can be manufactured. There are some exceptions though where a support structure is required for printing the object.

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II. CONSTRUCTION

The robotic system to be designed, is similar to a gantry crane, that is, it has three degrees of freedom for linear motion. It can travel along X, Y and Z axes; the orientation

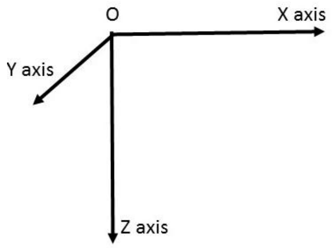

Figure 1 Orientation of axes for the system

of which is shown in the ***Fig. 1***. Out of the three axes, the X and the Y axes are formed by the upper frame in the form of bridges and girders which are supported by end mounts and the end carriages. Z axis formed by base platform guided upon suitable vertical rails. The construction of the system is shown in detail in ***Fig. 2***. The system is to be designed to be implemented as a 3d printer to give an output print of volume 200×200×200 mm^3.

A. X-axis

Refer ***Fig. 3***.The X axis is formed by a center carriage {1} sliding on two guide rods (girders){2,3} which are supported by end carriages{4,5} on each end. The necessary drive to move the center carriage along the X axis, is given by a belt {6} and pulley {7},{8} system is used, which is driven by a suitable motor {9}.

B. Y-axis.

Refer ***Fig. 4***.The end carriages of the X axis are supported by, and slide on the guide rods {10, 11} on each side of the frame. These guide rods (bridges), supported by four end mounts {12, 13, 14, and 15} form the Y axis of the system. The Y axis is driven by a motor {16}, belt {17} and pulley {18} system. Since the driving force needs to be equally distributed along both ends of the X axis, a transfer rod {19} is used, that distributes the driving torque or power equally at its both ends.

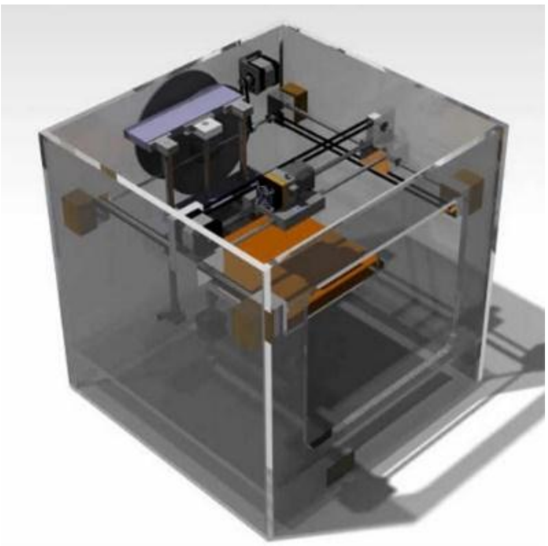

Figure 2 Construction of the robotic system

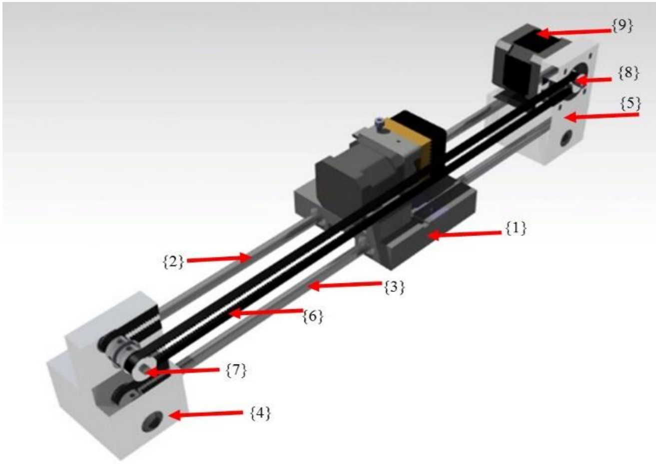

Figure 3 Structure of X axis

C. Z- axis

Refer ***Fig. 5***. The Z or vertical axis of the system is formed by the base platform {20} and the guide rods {21}, {22}. The motion in this axis is provided by a lead screw {23} and a meshing nut {24}, which is driven by a suitable motor {25}.

D. Extrusion system

Implementation of an extruder system allows the use of designed system as a 3D printer. An extruder consists of (a) Extrusion gear, (b) a stepper motor to drive the gear, (c) Heating block and (d) Nozzle. Based on the construction of the extruders, they can be classified as direct drive extruders and indirect extruders. In case of direct drive extruders, the whole assembly of parts mentioned above is one single unit and is mounted directly on the center carriage of the extruder. Whereas, in case of an indirect extrusion system, only the heater block and nozzle are mounted on the carriage while, the motor and the extrusion gear are mounted separately on the frame of the system. Direct drive extruders impose more load on the robotic system as compared to the indirect extruders. Thus, the system is designed to carry the weight of a direct drive extruder. ***Figure 6*** shows a direct drive extruder. MK8 direct drive extruder [1] will be equipped to implement the system as a 3D printer.

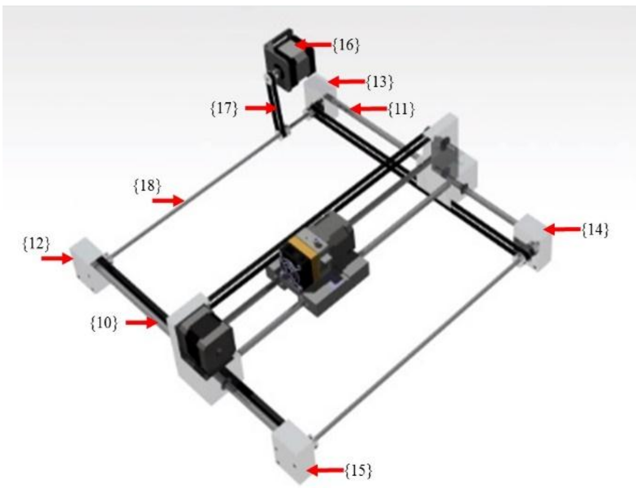

Figure 4 X-Y axes of the system

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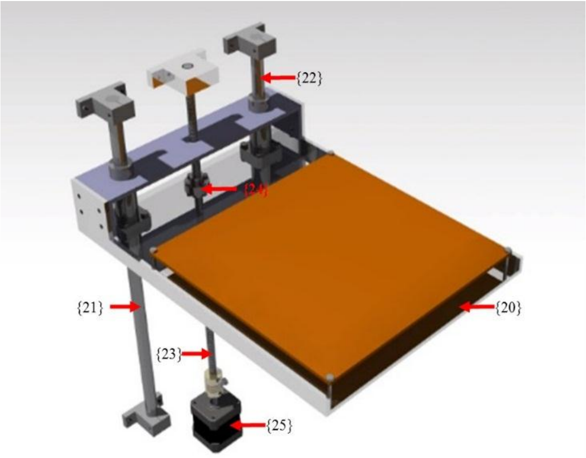

Figure 5 Structure of the Z axis of the system

III. DESIGN OF MECHANICAL SYSTEM

The entire robotic system is designed taking into consideration, the travel span along all the axes, and strength against the forces that will be imposed on the system. The components are checked depending on the ultimate tensile strength by verifying that calculated stress does not exceed the maximum stress allowable stress. The maximum allowable stress is given by:

$$F_a = \frac{UTS}{fos} \quad (1)$$

A. X and Y axes

The system is to be designed such that it can support the weight of the extrusion system, that is to be mounted on the center carriage of the X axis, and the self-weight of end carriages, girders, bridges and the end mounts. Dimensions of the system are decided based on required travel of the extrusion point of the nozzle in XY plane. The system can be designed by following the sequence as given bellow:

a. Center Carriage

It is a rectangular plate that supports the extruder, hence the dimensions if the base plane of the plate are decided such that it can fit the extruder.

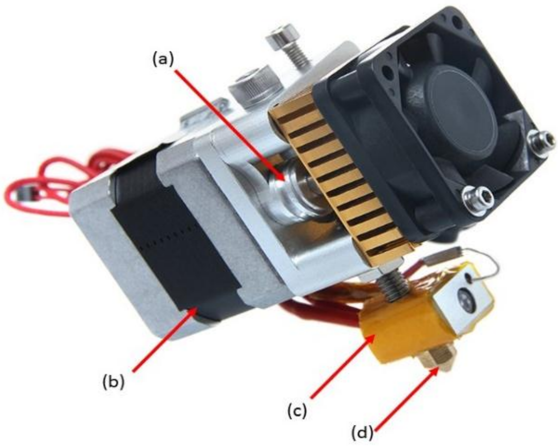

Figure 6 MK8 extruder [1]

The external dimensions of the extruder are: Length=83mm, Breadth= 42mm, Height =42mm and weighs 450gms. Thus, based on these dimensions and considering appropriate allowance for mounting the extruder on the carriage, the dimensions of the carriage are selected as follows: L=90mm, B=86mm . The required thickness of the plate is calculated by strength calculations by considering the bending stresses acting on the plate due to the force R_E= 4.415N exerted by the MK8 extruder. The plate is considered as a simply supported beam of length 90mm and cross section of (t_R x 86) mm. Aluminum is selected as the material for center carriage. Other materials such as ceramics or plastics can be used based on the cost budget and the availability of the material. Refer ***Fig. 7***.

$$M = \frac{R_E \times L}{4} \quad (2)$$

$= (4.415 \times 90) / 4$

$= 99.34$ N-mm.

$UTS_{Aluminum} = 310$ MPa.

Factor of safety (assumed) = 5.

Allowable stress, Fa = 310 / 5 = 62 MPa.

But, stress induced on the carriage $= \frac{M}{z}$ (3)

Where, $z = \frac{B \times t_R^2}{6}$ (4)

$= (86 \times t_R^2) / 6$

Thus, 62 = M/z

62 = 99.34 / z

This gives required thickness, $t_R = 0.4$ mm.

Thus, a feasible higher value of 1mm is selected as the thickness of the plate. Further, the carriage has to house linear bearings for providing smooth motion on guide rods. Thus, plate will be optimized after bearing selection.

a. Girders (X axis guide rods)

The length of the girders is selected by considering the required travel and clearances.

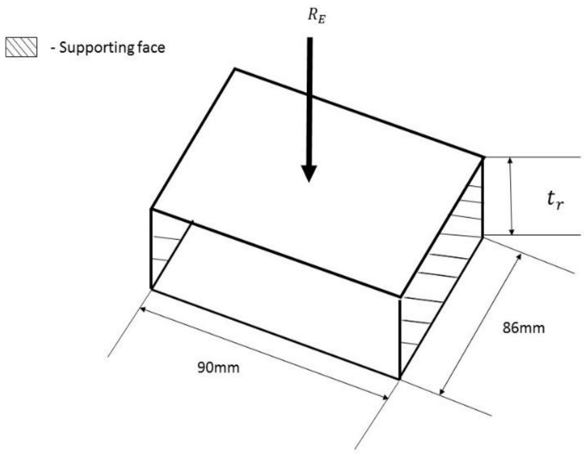

Figure 7 Loading of the center carriage

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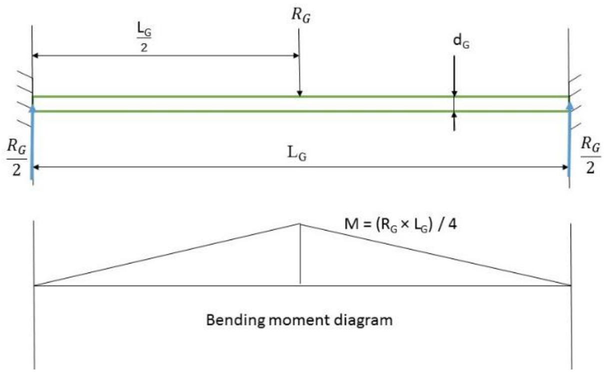

Figure 8 Loading of girder rod and its bending moment diagram

For a cross travel of 200 mm, the length of the girder rod is taken as 350mm. The rods are subjected to R_E and R_D. Since two rods are implemented, this load will be distributed equally among the two. Refer ***Fig. 8***.Thus each rod will be subjected to the half of the total load, which is given by:

$R_G = (R_E + R_D) / 2$ (5)

Where R_D is assumed to be = 0.8 × R_E = 0.8×4.415 = 3.532 N

R_G = (4.415 + 3.532) / 2 = 7.947/ 2 = 3.974 N

The required rod diameter is found by checking it against bending stress which is maximum when the load is at the center. The bending moment acting on the rod is given by:

$M = (R_G \times L_G) / 4$ (6)

= (3.974 × 350) / 4 = 347.68 N-mm

Bending stress = $\frac{M \times y}{I_G}$ (7)

Where, y = d_G /2 and

Moment of Inertia of the rod, $I_G = \frac{\pi \times d_G^4}{64}$ (8)

Designed bending stress should be less than or equal to allowable stress. Material used for guide rods is chrome hardened steel with UTS = 215 M-Pa. Considering a factor of safety of 5.

$$Fa = \frac{M \times y}{I_G} \quad (9)$$

$$\therefore 43 = \frac{(347.68 \times (d_G / 2))}{\left(\frac{\pi \times d_G^4}{64}\right)}$$

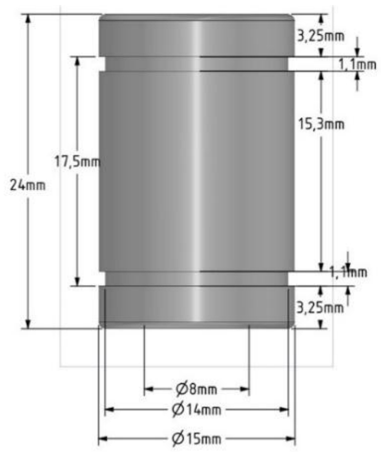

Figure 9 LM8UU bearing dimensions [2]

$\therefore d_G$ = 4.351 mm.

The required diameter of the guide rod is 4.351 mm. Based on the standard shaft sizes available 8mm diameter rod was implemented in the structure. The self-weight of the rod is found to be 1.52 N.

Linear bearings have to be implemented between the center carriage and the guide rods to allow smooth linear motion along the girders. Thus, linear bearings, LM8UU with dynamic capacity of 274N and a static capacity of 392N is selected. The detailed geometry of the bearing is shown ***Fig. 9***. In order to support these bearings the center carriage is optimized as shown in the ***Fig. 10***. The weight of the center carriage after these modifications is 2.77 N, which is less than the weight considered for guide rod strength calculation.

Linear actuation in X direction is provided by use of a stepper motor driven timing pulley and belt. GT2 pulley [3] with 2mm pitch, 20 teeth and 16mm diameter along with a 6mm width GT2 belt [3] are selected.

Force acting in the X direction that provides tension to the belt is the frictional resistance between bearings and the shaft. For anti-friction bearings, the co-efficient of friction for steel-steel contact is from 0.4 to 0.6 [4]. Assumed value = 0.5.

Thus, frictional resistance, $R_F = 2 \times \mu \times R_G$ (10)

= 2×0.5×3.974

= 3.974N

Torque required to be supplied by the motor

= R_F × Pulley radius (11)

= 3.974 × 8

= 31.792 N-mm= 0.318 kg-cm.

Thus, a NEMA 17 bipolar stepper motor is selected with torque capacity of 4.4 kg-cm. Self-weight of the motor is 0.365 kg.

a. End Carriages

End carriages support the girders on Y axis guide rods. The maximum will be imposed on an end carriages when the center carriage is at the closest point from it as shown in ***Fig. 11***. The maximum load acting on each of the end carriages due to X axis is Rx.

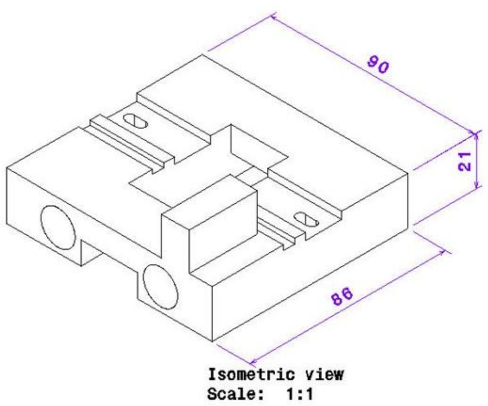

Figure 10 Optimized center carriage

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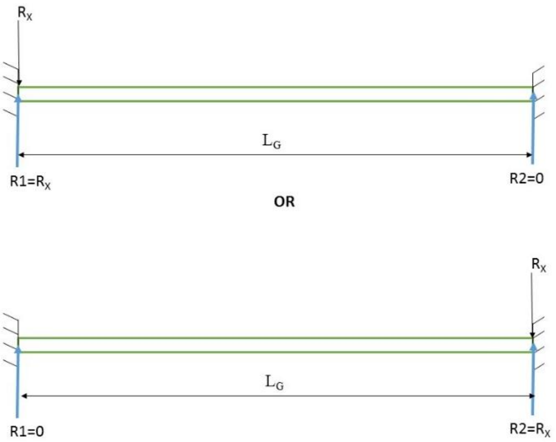

Figure 11 Maximum loading on the end carriages

Where, $R_X = 2\times R_G$ + Self weight of the rod. (12)
$= 7.948 + 1.52 \times 2$
$= 10.988$ N.

One of the end carriages has to support a stepper motor for actuating the motion in the X direction. Thus, total load acting on that end carriage,

$R_M = R_X$ + stepper motor weight $= 10.988 + 3.581$ (13)
$= 14.56$ N.

The load acting on its counterpart is simply the weight exerted by the X axis = 10.988.

Due to complexity of the geometry, the end carriages are designed by finite element analysis using ANSYS. The results are as shown in the ***Fig. 12*** and ***13*** for end carriage 1 and ***Fig. 14 and 15*** for end carriage 2.

It is seen that maximum imposed stress is less than allowable stress. Thus, it is a safe design. Self-weights of End carriages, 1 and 2 are 3.5N and 3.8 N respectively. Bearing LM8UU is implemented in the end carriages to allow smooth linear motion in Y direction.

b. Bridge (Y axis guide rods)

Y axis guide rods support the entire X axis structure. The length of these rods are selected based on the travel of center carriage and required clearance. For 200mm travel of the extrusion point, the length of the rod, L_B = 340mm.

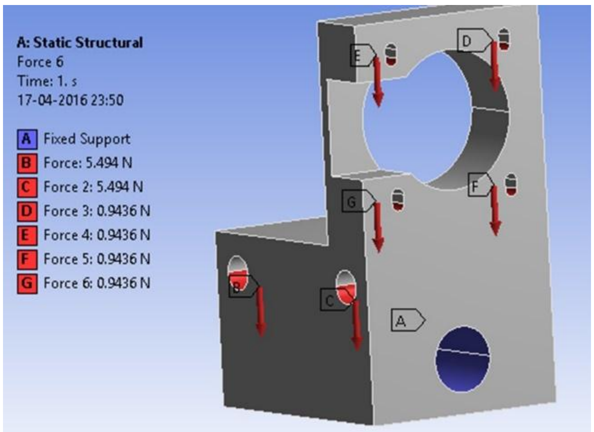

Figure 12 ANSYS simulation of loading of end carriage 1

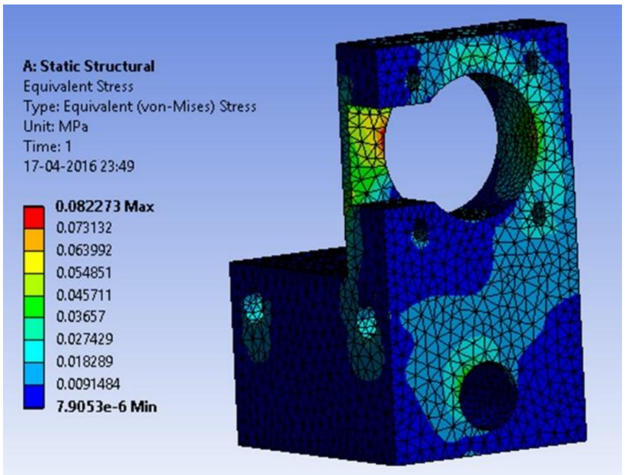

Figure 13 ANSYS simulation of Equivalent stress on end carriage1

The maximum load acting on each rod of the bridge,

$R_B = R_M$ + Self-weight of the Motor carriage (14)
$= 14.56 + 3.5$
$= 18.06$ N

$M = (R_B \times L_B) / 4$ (15)
$= (18.06 \times 340) / 4$
$= 1535.1$ N-mm

$$\because F_a = \frac{M \times y}{I_B} \quad (16)$$

$$43 = \frac{(1535.1 \times (d_B/2))}{\left(\frac{\pi \times d_B^4}{64}\right)}$$

$\therefore d_B = 7.137$ mm

Thus, shafts of diameter 8mm are selected for bridge guide rods. The self-weight of these rods is found to be 1.5284N each.

c. Transfer rod

It is implemented to transfer the motion of a single motor to both the sides of the Y axis. 8mm diameter rods are selected. GT2 pulleys and belts are implemented on the transfer rod as shown in the ***Fig. 4***. Self-weight of transfer rods = 1.55N each. 628RS ball bearing with 8mm bore diameter is selected for smooth rotational motion of the rod.

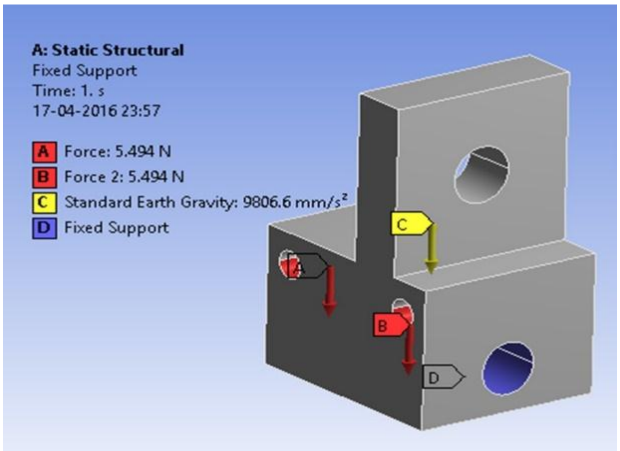

Figure 14 ANSYS simulation of loading of end carriage 2

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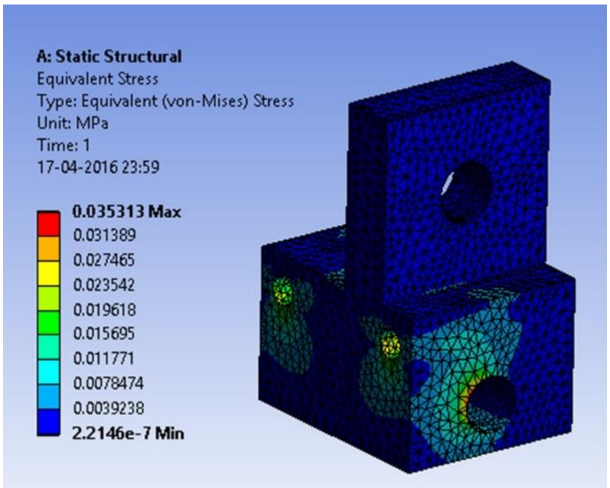

Figure 15 ANSYS simulation of Equivalent stress on end carriage2

d. End Mounts

Four End mounts support the entire X-Y frame along with transfer rods to transmit motor power along Y axis. Thus, the load acting on each of the end mounts,

R_{EM} = (R_M+ Self weight of end carriages +
2×self-weight of Y axis rods+
2× self-weight of transfer rods) / 4 (17)

R_{EM} =14.56 +3.5+3.8+ 2×1.528+2×1.55
= 28.016 / 4
= 7.004 N

The end mounts are designed by finite element analysis by using ANSYS. Refer ***Fig. 16*** and ***Fig. 17*** for the results. The induced stress is lower that allowable stress (63 MPa for Aluminum). Hence, the design is safe.

Motor selection for Y direction:

Total frictional resistance in in Y direction
= R_Y = 4×µ× R_{EM} (18)
= 4 ×0.5×7.004
= 14.008N

Torque required to overcome this frictional resistance
= R_Y × Pulley radius (19)
= 14.008 × 8
=112.064 N-mm= 1.121 Kg-cm

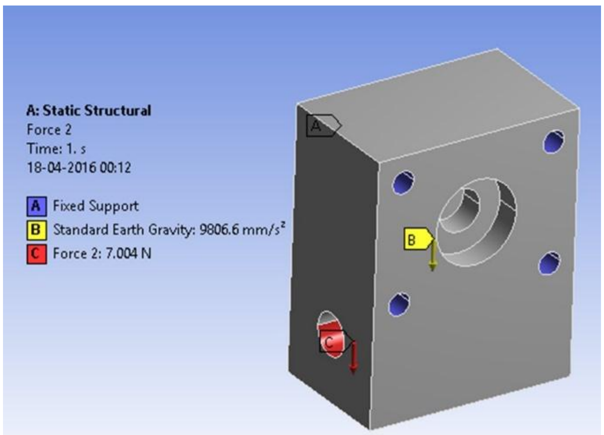

Figure 16 ANSYS simulation of loading of an end mount

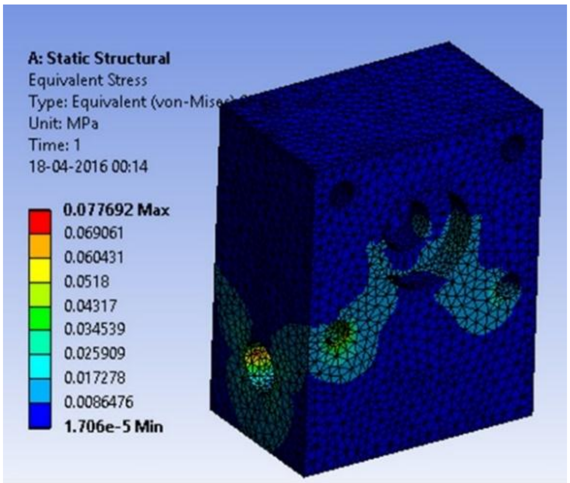

Figure 17 ANSYS simulation of Equivalent stress on an end mount

Thus, a NEMA 17 bipolar stepper motor is selected with torque capacity of 4.4 kg-cm. Self-weight of the motor is 0.365 kg.

B. Z axis

The z axis mechanism is designed to carry the load of the product extruded by the extrusion system. The base platform is considered as a cantilever plate supported by the vertical guide rods. Refer ***Fig. 18***.

a. *Base Plate*

The dimensions of the base plate are selected based on the maximum dimensions of the print required and the space clearances with respect to other components. Required print size is 200×200×200 mm.

Thus, by considering other space clearances the plate size selected B_z=224mm and L_z=315 mm. The Base plate supports a heated bed, with weight 3.9 N, required for 3d printing applications. The maximum design load imposed on the base plate is assumed as 30N considering 2.5 kg print output.

Total Point Load in z direction = F_z = 30 N is at a distance 207mm from the support as shown in the ***Fig. 18***.

Bending Moment acting on the Beam,
M= F_z ×207= 30×207= 6210 N-mm (20)

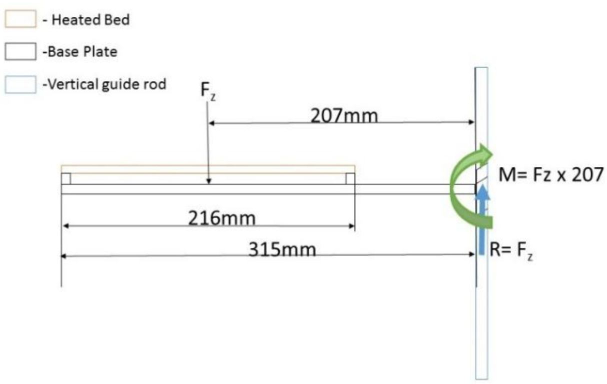

Figure 18 Force distribution on Z axis

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Aluminum material with UTS= 315 MPa is selected for bed. Considering a factor of safety of 5,

Allowable bending stress = 315/ 5 = 63 MPa.

$$\therefore 63 = \frac{M \times y}{I_Z} = \frac{(6210 \times (T/2))}{\frac{224 \times T^3}{12}} \quad (21)$$

T=1.625 mm.

Thus, an aluminum plate of 3mm thickness and 224×315mm^2 base plane dimensions is used. Self-weight of the plate is found to be =0.4 Kg= 4N.

b. Vertical Guide rods

Vertical travel required = 200mm. Thus, by considering clearance to occupy the supporting mounts, 350mm length rods are selected as z axis guide rods. These rods are subjected to bending as well as an axial force as shown in the Fig. 18.

Thus, the diameter of the rods is calculated by using formula [5]:

$$D_z{}^3 = \frac{16}{\pi \times \tau} \times (K_b \times M_b + \alpha \frac{F_z \times D_Z}{8}) \quad (21)$$

$$\text{Where, } \tau = \frac{UTS_{STEEL}}{2 \times Factor\ of\ Safety} = \frac{215}{2 \times 5} = 21.5 \text{ MPa} \quad (22)$$

K_b = 1.5 for impact loading
M_b =6210 / 2= 3105 N-mm
α = 1 for tensile loading
F_z= 30/2 = 15N

By substitution, the value of D_z = 10.35 mm.

Thus, rods of diameter 12mm are selected for Z-axis guide rods. Linear Flange bearings LMK12UU are selected to provide smooth linear motion in Z direction. They are fixed on the base plate and provide support to the bed as well.

c. *Leadscrew rod*

8mm trapezoidal threaded leadscrew rod of 350 mm length and meshing nut with 2mm pitch is selected. The nut is fixed on to the base plate. The leadscrew revolves over the threads of the nut to impart linear motion in Z direction. Lead screw is driven by a stepper motor.

Torque required to raise the load [6]

$$= \frac{F \times d_l}{2} \times \frac{(l + \pi \times \mu \times d_l)}{(\pi \times d_l - \mu \times l)} \quad (23)$$

Torque required to lower the load [6]

$$= \frac{F \times d_l}{2} \times \frac{(\pi \times \mu \times d_l - l)}{(\pi \times d_l + \mu \times l)} \quad (24)$$

Where,
d_l = 8mm
l= Axial Pitch = 2mm
μ= Coefficient of friction between the lead screw and nut.
= 0.19 for steel screw and brass nut. [6]

The load to be raised or lowered can be found as:
$F = F_z + R_z$

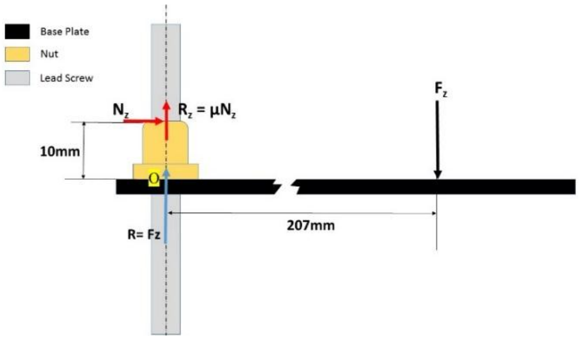

Figure 19 Loading on the nut and lead screw

Where, N_Z is the force on the nut, due to bending moment, imposed by the cantilever plate. Refer ***Fig. 19***.

At equilibrium, sum of all the moments at a point O is zero.

$$\therefore F_z \times 207 = N_z \times 10 \quad (25)$$

$\therefore N_z = F_z \times 207 / 10$
= 30× 20.7
= 621N

Now, $R_z = \mu N_z$ (26)
= 0.19 ×621
= 117.99 N

$\therefore F = R_z + F_z$
= 118 + 30
= 148N

By substituting above values in equation (23) and (24) we get,
Torque required to raise the load=16.2 N-cm = 1.62 Kg-cm.
Torque required to lower the load= 6.64N-cm = 0.664 Kg-cm

Thus, a NEMA 17 bipolar stepper motor is selected with torque capacity of 5.5 kg-cm. Self-weight of the motor is 0.365 kg.

The entire assembly is mounted on a box type frame which can be built by wood, acrylic, aluminum or any other material based on the budget and availability of the material. The dimensions of the external frame are carefully selected to fit in all the mechanical and electronic control system of the robot.

IV. CONTROL SYSTEM

In order to control the motion of the extruder in X, Y and Z direction as well as the material feed rate, it is necessary to control the actuation of the respective stepper motors. This control is provided by Arduino Mega 2560 [7] microcontroller. The firmware is installed on the Arduino board by connecting it to a personal computer and writing the data into its ROM. Other electronics necessary for control of the system are as stated below.

A. RAMPS 1.4

It is a control board that allows connection of Arduino Mega 2560 to all other electronic components.

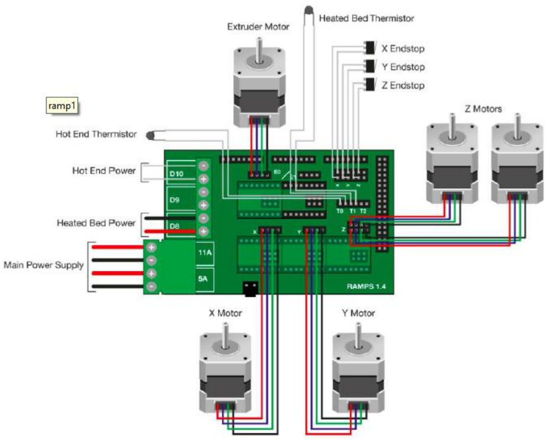

Figure 20 Connection of Electronics to RAMPS 1.4[8]

It can control up to five stepper motors along with heat sensors for extruder, LCD module and External memory stick module. **Figure 20** shows connections on RAMPS 1.4 [8]

B. Stepper Motor drivers

It is an electronic chip implemented to control the speed and stepping angle of the motors. Polulu A4988 [8] drivers are selected. Four stepper motor drivers are implemented to control the X, Y, Z axes and the extruder.

C. LCD module

It acts as a communication device between the user and Arduino. It has a knob to change or select any entity displayed on the screen. Some Modules have an inbuilt memory card reader.

D. Firmware

Marlin [9] and Repetier [10] are two of the most widely used open source firmware, based on Arduino language, for control of a 3D printer. Based on the requirements of the user, firmware needs to be configured. Marlin requires all the communication to be done on the board itself via LCD knobs, whereas, in case of Repetier, a personal computer can be used additionally for communication with the controller. Repetier also provides real-time feedback of ongoing process of the system.Firmware used this system is the Marlin.

The Marlin firmware is available free of cost over the Internet. The marlin.ino file needs to be opened in the Arduino IDE to make the configuration changes on the basis of your 3D printer dimensions and the characteristics of the electronic components used.

Some on the common settings include defining the following:

1. Baud rate (speed of communication between the computer and electronic board).
2. Motherboard to be used (For Example: Arduino Mega 2560).
3. Number of Extruders.
4. Temperature Sensor settings.
5. Minimum and maximum temperature limits of the extruder hot end and the heated bed.
6. End stop settings.
7. Maximum and minimum travel limits on all the three axis
8. Travelling speed and acceleration.
9. Axis steps per unit (number of steps required on the stepper motor to move along the axis by 1mm).
10. Stepper motor direction (inverse or not).

V. WORKING PROCEDURE

The prototype or object that needs to be printed is designed by use of appropriate computer aided designing software. This design is converted into Standard Tessellation Language (STL) format. This file is sliced, by use of dedicated software, into various horizontal planes of desired thickness based on the resolution of the print required. This data is then converted to motion control data by the firmware installed on the microcontroller and this controls all motions in the system accordingly. The motors are actuated to move X, Y and Z axes respectively until the final product is obtained.

VI. CONCLUSION

A detailed procedure required to design a three axis robotic mechanism is described that can be referred to, while designing a 3D printer or any other application involving use of three axis motion mechanisms such as a laser cutting machine or a milling machine by replacing the extruder module with a laser cutting module or a milling cutter respectively.

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