IIT Madras

Centre For Innovation

CODE: SCARA Project

3D-Printing Club

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- Avid Feluda reader
- Loves chicken

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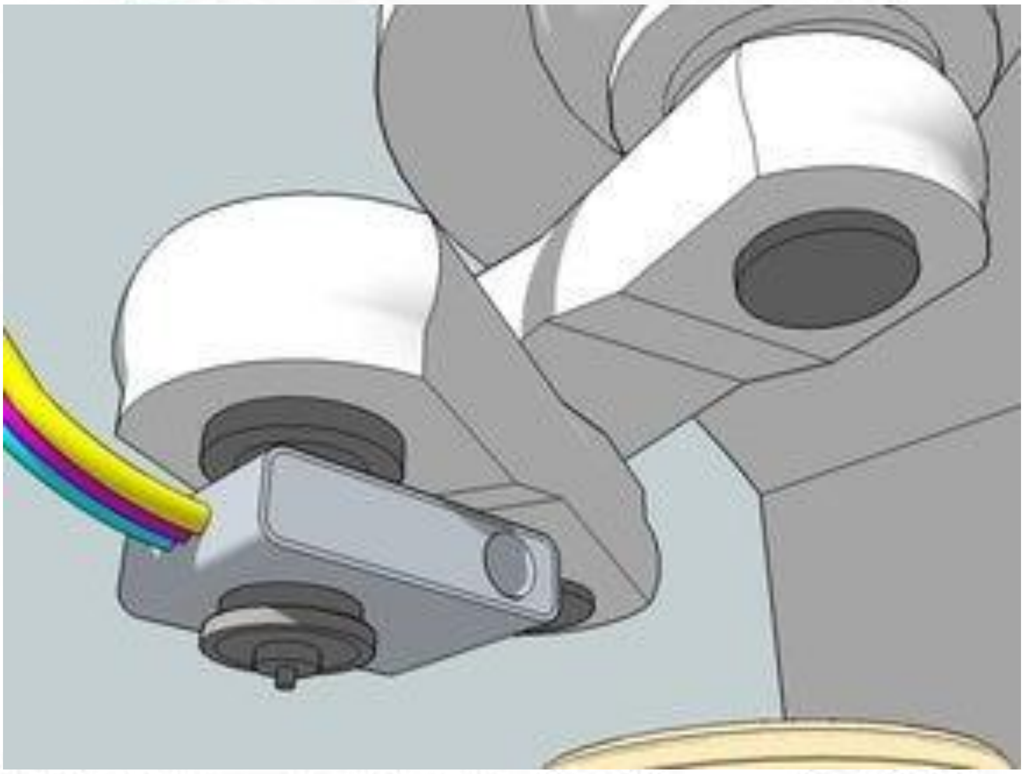
- Bong Boy, Lives in Mumbai
- Plays and enjoys Football, Basketball, Swimming, Painting
- Sci-Fi, ++ Movie Buff
- Outbound, Enthu guy.

CODE: SCARA PROJECT



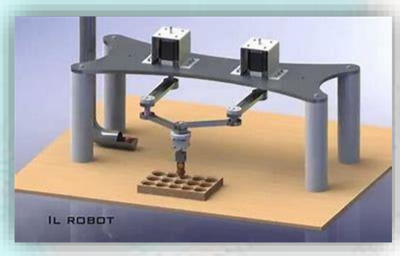
30-05-2020

Table of contents.

i. Overview of project

Selective Compliant Assembly Robot Arm has found its extensive use in the machine and manufacturing industry.
Be it assembly lines in automation systems, object transfers in small scale or certain custom builds for fulfilling custom demands, SCARA is arguably the best, even in deposition tasks due to its primary job of installing electrical components over circuit boards.

The completion of SCARA Printing build would enable to open up ideas for further kinds of builds The major focus would be over the versatility of the arms.



By virtue of the SCARA's parallel-axis joint layout, the arm is slightly compliant in the X-Y direction but rigid in the 'Z' direction, hence the term: Selective Compliant.
The second attribute of the SCARA is the jointed two-link arm layout similar to our human arms, hence the often-used term, Articulated.
The project also aims to question to the theoretical max speed of a printer. which is often limited to the use of type of plastic.

The base firmware is Marlin, with little tweaks and practical parameters we believe it to be an absolute success. We have also looked into other firmwares, namely Wangasamas.
In effect of understanding and implementing we have looked at various commercial builds and also the other SCARA builds available in the market.

Talking of automation assembly lines, serial manipulators are the common industrial robots, designed as series of links connected by motor-actuated joints extending from base to an end-effector (platform). On the other hand, parallel manipulator uses several computer-controlled serial chains to support the platform.

ii. Brief history

SCARA (pre-3DP) was presented by Sankyo Seiki, Pentel and NEC in 1981 primarily for assembly robots, mainly under Hiroshi Makino, professor at University of Yamanashi.
SCARAs are faster than cartesian systems, but at the same instant they are expensive, and the controlling software requires inverse kinematics for linear interpolation.

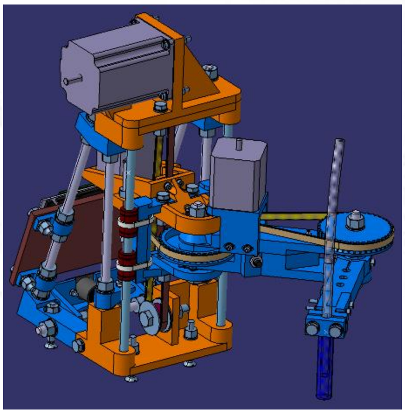
The actual revolution started with RepRap Morgan, an open source 3D printer. The first arm designed by Quentin Harley, South African engineer. In 2013 the Morgan won HumanityPlus Uplift Personal Manufacturing prize and secured third place in the Gauteng Accelerator Program.

The Morgan printer was named after Thomas Hunt Morgan.

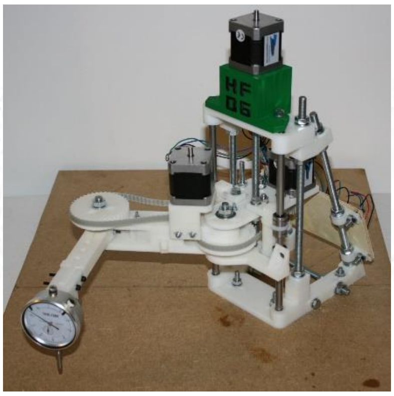
There are four version of RepRap Morgan, the Morgan v1 (CD-Thomas), Morgan Pro, Morgan Mega and Morgan Pro 2 (CD-Lilian).
The Morgan Pro 3 released recently has ton of improvements over the Pro2.

Speaking of RepRap movement, the scara builds that have been documented in the tree are-

Helium Frog Scara,



IN theory…



IN reality…

iii.Background work done

The background job done include establishing all basic fundamentals within our team. Also taking care of practical knowledge and theory while searching up various SCARA builds and their advantages.

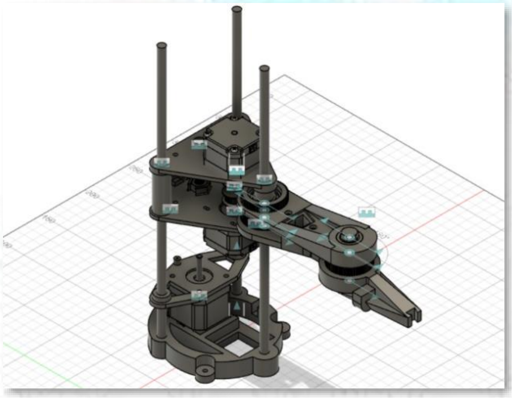
Arduino being the major part taker, we have also done Arduino IDE Tutorials to give everyone a basic knowledge of Arduino commands, which are a little different.

Cura is a must for slicing projects. And our club heads have given the utmost knowledge to all its enthusiasts. With obviously keeping in mind the Ultimaker.

The firmware is Marlin, Arduino board compatible, long time support and moreover open-source.

The functionality is also of importance, and hence the mechanism of the single arm SCARA, joints plus arm work was explained in a GMeet session by Shreyansh and Sriram.

Kinematic Modeling.



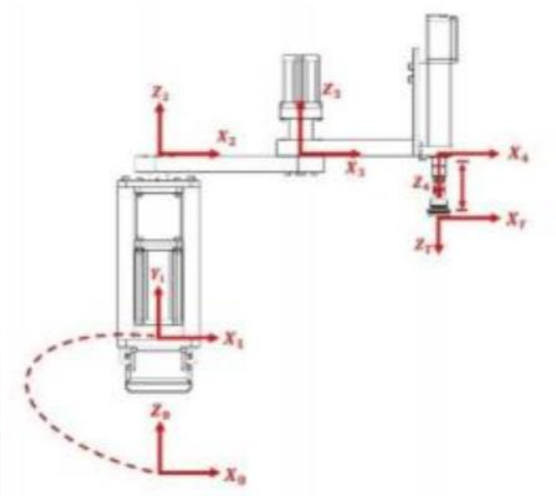
The Single Arm SCARA.

Forward kinematics is process of determination the position and orientation of end effector given values for joints variables of robot. Inverse kinematics is inverse process that determines values of joints variables for given position and orientation of robot’s end effector.

Forward Kinematics:

With rigidly attached frame, the DH parameters:

i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	π/2	d_1	0
2	0	-π/2	l_1= 0.363m	θ_2
3	l_2= 0.265m	0	0	θ_3
4	l_3= 0.2536 m	π	d_4	0
5	0	0	d_5 = 0.11m	0



Using general form of transformation matrix that transforms vectors

$$ {}^{i-1}_{\ \ i}T = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{i-1} \\ \sin\theta_i \cos\alpha_{i-1} & \cos\theta_i \cos\alpha_{i-1} & -\sin\alpha_{i-1} & -\sin\alpha_{i-1} d_i \\ \sin\theta_i \sin\alpha_{i-1} & \cos\theta_i \sin\alpha_{i-1} & \cos\alpha_{i-1} & \cos\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Substituting parameters, and finally obtaining:

$$ {}^{0}_{T}T = \begin{bmatrix} c_\phi & -s_\phi & 0 & x \\ s_\phi & c_\phi & 0 & y \\ r_{31} & r_{32} & -1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

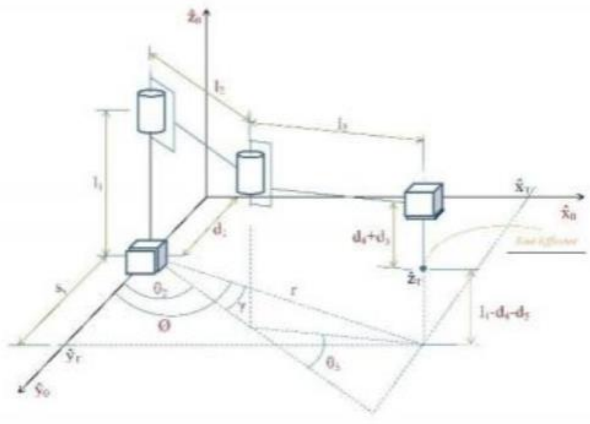
Where

$$ \begin{bmatrix} x \\ y \\ z \\ \phi \end{bmatrix} = \begin{bmatrix} l_2 c_2 + l_3 c_{23} \\ l_2 s_2 + l_3 s_{23} - d_1 \\ l_1 - d_4 - d_5 \\ \theta_2 + \theta_3 \end{bmatrix} $$

Parameter Nomenclature, in the end.

Inverse Kinematics:

Derived by solving for values of two joints parameters (θ2, θ3) and values of two links parameters (d1,d4).



Applying the geometric representation of robot, we got these relationships of variables:

$$\begin{cases} d_4 = l_1 - z_T - d_5 \\ d_1 = y_T - s_y = where\ s_y = l_2 s_2 + l_3 s_{23} \\ \theta_3 = a\tan 2(\pm\sqrt{1 - c_3^2}, c_3)\, where\ c_3 = \dfrac{s_y^2 + x_T^2 - l_2^2 - l_3^2}{2 l_2 l_3} \\ \theta_2 = a\tan 2(s_y, x_T) - a\tan 2(l_3 s_3, l_2 + l_3 c_3) \end{cases}$$

With these relationships, the only one parameter that can be solved is d4, where other three parameter is dependent on each other and related to two coordinate vales of robot's end effector.

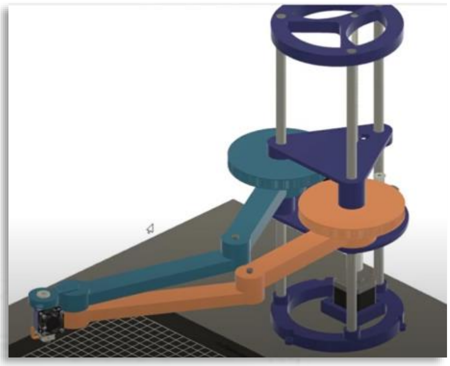
A solution proposed is to give an arbitrary value for d1. Three levels of d1 is applied (d1=0, 0.3, 0.6). The value of sy was solved. Eventually equations for θ3 and θ2 could be solved.

<u>Parameter nomenclature:.</u>

Symbol	Description	Unit
a_{i-1}	The distance from $\hat{Z}_i$ to $\hat{Z}_{i-1}$ measured along $\hat{X}_i$	m
α_{i-1}	The angle from $\hat{Z}_i$ to $\hat{Z}_{i-1}$ measured about $\hat{X}_i$	rad
d_i	The distance from $\hat{X}_{i-1}$ to $\hat{X}_i$ measured along $\hat{Z}_i$	m
θ_i	The angle from $\hat{X}_{i-1}$ to $\hat{X}_i$ measured about $\hat{Z}_i$	rad
${}^{i-1}_{i}T$	Transformations matrix that transforms vectors defined in{i} to their description in{i-1}	-
t_2	$\tan\theta_2$	-
c_2	$\cos\theta_2$	-
s_2	$\sin\theta_2$	-
c_{23}	$\cos(\theta_2+\theta_3)$	-
s_{23}	$\sin(\theta_2+\theta_3)$	-
x	$\hat{x}$ vector of end effector attached frame related to zero frame	m
y	$\hat{y}$ vector of end effector attached frame related to zero frame	m
z	$\hat{z}$ vector of end effector attached frame related to zero frame	m
θ	Rotation angle of end effector attached frame related to zero frame	rad

After learning about single arm SCARA. The project cult also looked up at 5-arm SCARA, led by Sohini.

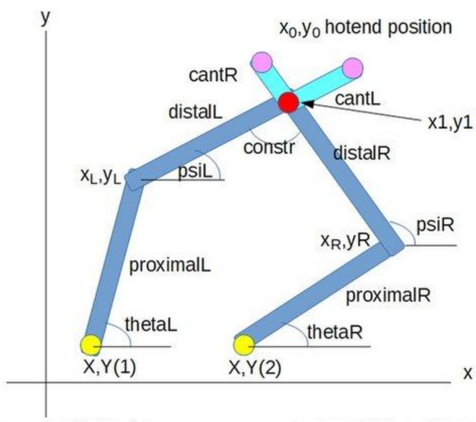
The 5-Arm SCARA.



A 5 Bar SCARA has 5 bars: one between the actuators, and two arms on each side left and right.

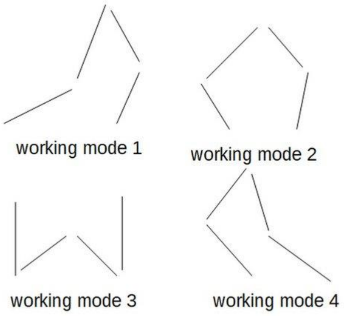
Step 1: Construction and naming.

- The names in the image are used in this documentation.
- The red dot is the hotend position, the yellow dots represent the actuators/steppers
- At top are optional cantilevered arms with hotend positions at the end.
- The positions of the actuators are defined by M669 X and Y parameters.



- proximalL, distalL are the left arms in mm, proximalR and distalR the right ones. theta and psi left (L) and right (R) are degrees measured from the x axis. The optional cantilevered arm of distalL is of length cantL, for distalR it is cantR.
- constr is a constraint angle: if the angle is too flat, the SCARA cannot be moved (singularity). If it is too small, the x0,y0 position becomes undefined.
- x0,y0 is the hotend point, xL,yL and xR,yR the left and right hinges.

Step 2: Working Modes.



- A point x0, y0 can be accessed with up to 4 different constellations for the proximal and distal arms. Every arm pair proximal + distal can be bent "inside" and "outside".

- Default is mode 1. It has a bigger rectangular print region than mode 2 and doesn't need a distance to the actuators.

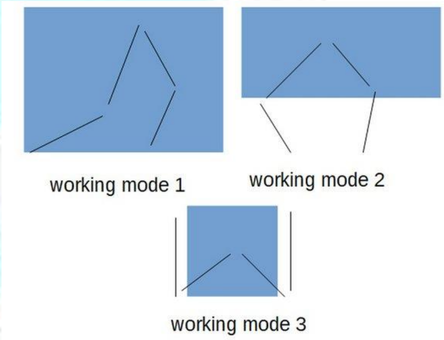
- Care must be taken to avoid areas called singularity, which are unprintable areas because arm angles are too flat or small and the movement is undefined.

Step 3: Print Area.

- The print area depends on the arms lengths, the distance between the Actuators and the constraints.

- Approximately, the print area of Working Mode 1 is an area like shown in the image. The exact area is calculated in the method IsReachable.

- Mode 2 the printable area is farther away from the proximal arms.



- Mode 3 is under the actuators and difficult to be used with the hotend above the end point.

- Mode 4 is symmetrical to mode 1 at the Y axis.

- The exact print areas have more complex shapes.

- The actuator distance and arm lengths have influence on print area, speed and precision.

Step 4: Firmware Calculations.

- Forward kinematics is the calculation of x0/y0 from the two proximal angles thetaL and thetaR. The code is defined in the method MotorStepsToCartesian.

- Inverse kinematics is the calculation of the two proximal angles thetaL and thetaR from a given x0/y0. There are 0 to 4 possible solutions. The algorithm will get the solution for the given working mode. The code is defined in the method CartesianToMotorSteps.

- To calculate the printable area, specific constraints must match. The constraints and valid print area are defined in the IsReachable method.

Step 5: M669 geometry configuration.

- Geometry settings are defined with M669, analoguous to the Scara setup. Z axis and stepper properties are defined like a Cartesian printer. K9 is the printer type mode.

- Xnnn:mmm and Ynnn:mmm X and Y coordinates of the left and right proximal actuator axes. E.g. X0:100.5 Y0:0 means 100.5 apart and both on the y axis.

- Lnnn working mode: 0, 1, 2, 3 or 4, see image above. 0 is using all modes and switch if necessary, default is L1. Supported modes so far are modes 1, 2 and 4.

- Pnnn:mmm proximal arm lengths: nnn is left and mmm is right proximal in mm. Can be fractions of mm, e.g. P300.5:299.8. The lengths are from the middle of one joint to the other one.

- Dnnn:mmm[:ppp:qqq] distal arm lengths: nnn is left distal arm, mmm the right distal arm in mm, fractions are possible. E. g. D200:230.5. Lengths is measured from middle of joints. The optional parameters p and q see below for cantilevered arm. Currently, all 4 parameters must be set, so with uncantilevered hotends set :0:0 as parameters 3 and 4.

- Bnnn:mmm defines the degrees of the homing end positions homingAngleL and R in respect to the x axis. The setting must be valid in respect to print area and other constraints. The values can be fractions of degrees. For workmode 1, default is B20:10, for workmode 2 it is B110:20, for workmode 4 it is B110:100

- Annn:mmm:ppp:qqq:rrr:sss nnn is the minimum angle between the distal arms (constr in the first image) in degrees, mmm the maximum. ppp:qqq is the minimum and maximum angle between proximal and distal arms on the left. rrr:sss between proximl and distal on right. The mechanical construction might set limits. Default is A15:165:0:360:0:360

- Znnn:mmm:ppp:qqq optional to define the print area as rectangle. Z0:0:500:200 means from 0,0 to 500,200. The user is responsible to define a reachable area.

- comment on Z: *) Meant: if the printer moves from A to B, it may not move through an area where the movement is not possible in the given working mode.

- Snnn Maximum segments per second (optional).

- Tnnn Minimum segment length (optional).

- With exception of K and L, all parameter values can include decimal parts.

- Cnnn:mmm:ppp:qqq is the minimal and maximal angle left and right of the actuators. C10:100:15:200 means the left stepper can have angle between 10 and 100 degree, the right one between 15 and 200. Default is C10:170:10:170. The variables are called actuatorAngleLMin etc.

Step 7: Calculation of Actuator settings M92.

- For precision, it is preferable to use a gear at the actuator, between stepper and first hinge of the proximal arm. The higher the gear ratio, the better the precision (but slower maximum speed). A ratio between 1:5 and 1:30 is a good starting value.

- The properties are set by the values of microstepping in M320 and setting the X and Y properties in M92:

- M92 = microsteps / motordeg * bigpulleyteeth / stepperpulleyteeth

- E.g. 128 microsteps, 1.8 degree steppers, 90 teeth at hinges, 20 teeth at steppers: M350 X128 Y128 ... and M92 should be 128/1.8*90/20=320, results in M92 X320 Y320 ...

- Example 2: M350 X128 Y128 , 1.8 Stepper, 16 Stepper teeth, 300 mm diameter wheel: 128/1.8*471/16=2093, results in M92 X2093 Y2093...

Step 8: Example Config File.

- M569 P0 S1 ; Drive 0 (X) goes forwards
  M569 P1 S1 ; Drive 1 (Y) goes forwards
  M569 P2 S1 ; Drive 2 (Z) goes forwards
  M569 P3 S1 ; Drive 3 (E0) goes forwards

- M574 X1 Y1 Z0 S1 ; proximal L and R homing switches trigger when the arm is at M669 B positions and are active high

- M669 K9 X0:100 Y0:0 P300:300 D300:300:0:0 ; arms are 300 mm long, actuators are 100 mm apart, other parameters take defaults. (Be aware, that D always needs 4 Parameters)

- M203 X10000 Y10000 Z300 E3600 ; maximum speeds mm/minute
  M906 X800 Y800 Z800 E800 ; set motor currents (mA)

Step 9: Homing Files.

- The endstops are activated when the proximal arms are at a specific angle. The endstops can be activated from both sides of movement. The homing strategy decides which side defines the angle precisely.

- When starting the printer, the axes shall be roughly near the endstops.

- The steppers turn some degree left and right until the end stop is reached.

- The endstops and M669 B parameter define the theta angles. With e.g. M669 B90:90, when reaching both endstops, both steppers are at position 90 degree each for thetaL and thetaR.

iv. Bill Of Materials

The Bill of Materials for single arm SCARA, we have searched various websites to look for our parts, features within, keeping in mind the availability within our nation.

S.NO	Particulars	Quantity	Per Unit Cost	Purchase Link	Part No	Weight
1	Stepper Slim	2	Rs. 543	https://robokits.	RMCS-1023	220 gms
2	MKS Gen 1.4 Board	1	Rs. 2400	https://robu.in/p	-	110 gms
	(or) SKR 1.4 Turbo +	1	Rs. 3837	https://www.ubu	KINGPRINT-ZZB0(	-
	TMC2209 driver	1	Rs. 1049	https://robu.in/p	-	-
3	Pulley	2	Rs. 148	https://robu.in/p	-	6 gms
4	Timing Belt + 2 Pulleys (Set)	1	Rs. 540	https://robu.in/p	-	155 gms
5	160mm Belt	1	Rs.89	https://robu.in/p	-	85 gms
6	Mech Endstop	3	Rs. 300 (per 4 pcs)	https://www.am	BG07Q131	40 gms
7	LCD	1	Rs.749	https://robu.in/p	-	240 gms
8	12V DC	1	Rs. 649	https://robu.in/p	Orange 12V 5A	295 gms
9	Stepper	1	Rs. 660	https://robokits.	RMCS-1010	300 gms
10	608RS ball bearing - 2pcs	2	Rs. 49 (per 2 pcs)	https://robu.in/p	-	85 gms
11	Threaded rod M8	1	Rs. 120	https://www.diy-	-	-
12	Smooth rod 8mm, 100cm	3	Rs. 390	https://robokits.	RKI-6024	-
13	6902ZZ Bearing 15x28x7	3	Rs. 62.5	https://robu.in/p	6902ZZ	40 gms
14	200*200 HeatBed	1	Rs. 1500	https://www.am	CHPSS565	160 gms
15	E3D-V6	1	Rs. 800	https://www.am	CHPSS531	60 gms
16	MK8 Extruder	1	Rs. 295	https://compoin	-	60 gms
17	Dupont connector kit	1	Rs. 549	https://robu.in/p	-	-
18	M3x15 nut bolt washer set	2	Rs. 59 (for 20 pcs)	https://robu.in/p	-	-
19	M3x20 nut bolt washer set	4	Rs. 59 (for 20 pcs)	https://robu.in/p	-	-
20	M3x25 nut bolt washer set	2	Rs. 59 (for 20 pcs)	https://robu.in/p	-	-
21	M3x50 nut bolt washer set	3	Rs. 59 (for 15 pcs)	https://robu.in/p	-	-
22	M3x6 nut bolt washer set	6	Rs. 59 (for 25 pcs)	https://robu.in/p	-	-
23	M3x8 nut bolt washer set	14	Rs. 59 (for 25 pcs)	https://robu.in/p	-	-
24	M8 Nut	3	Rs. 170 (for 25 pcs)	https://www.am	-	-
25	M8x45 bolt	1	Rs. 10	https://indialoca	-	-
26	M8 washer	1	Rs. 1	https://indialoca	-	-

More involved--> BOM SCARA - Google Sheets //single arm

BOM SCARA - Google Sheets //5 arm

S.NO	Particulars	Quantity	Total Cost (Rs)	Purchase Link
1	LML12UU- like bearings	3	390	https://robu.in/product/lm12uu-op-1
2	12 mm smooth rods 100cm	3	2697	https://robu.in/product/1000-mm-lor
3	6808 bearings	4	450	https://www.shakedeal.com/nsk-68
4	8mm thrust bearings	4	533	https://www.amazon.com/uxcell-F8
5	12 mm threaded rod	1	199	https://www.diy-india.com/products
6	48mm 0.9 degree NEMA 17 motor	3	2997	https://robu.in/product/nema17-4-4-
7	20 Teeth 5mm Bore GT2 Timing Pulley for 10mm	2	316	https://projectpoint.in/index.php?rou
8	GT2 10 mm open timing belt 2000mm	1	360	https://ifuturetech.org/product/gt2-1
9	E3D V6 Hotend	1	799	https://www.amazon.in/3D-Innovatic
10	3060 T slot aluminium profile	1	680	https://www.indiamart.com/proddeta
11	MKS Gen 1.4 Board	1	2400	https://robu.in/product/1-4-mks-gen
12	12V DC	1	649	https://robu.in/product/orange-ac-1(
13	MK8 Extruder	1	295	https://compoindia.com/product/rigl
14	Nuts, bolts, washers	-	~100	https://robu.in/product-category/me

v. CAD files

The CAD files have been extensively, created using Fusion360. Consisting of various modeled parts.

The files have been uploaded to the 3DP GitHub club drive.

Each individual part was scaled to appropriate dimensions, then measurements were taken to model all of the components of the build using Autodesk fusion.

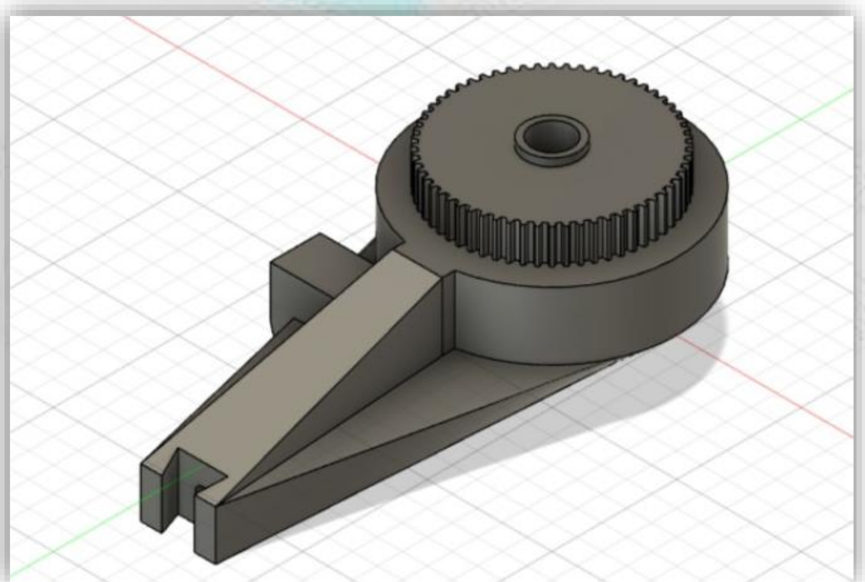
Assembly of each components was done using appropriate joints, motions, constraints, etc… in a totally step wise manner.

There are total 16 CAD files to be printed. The major ones :-

FOR SINGLE ARM SCARA →

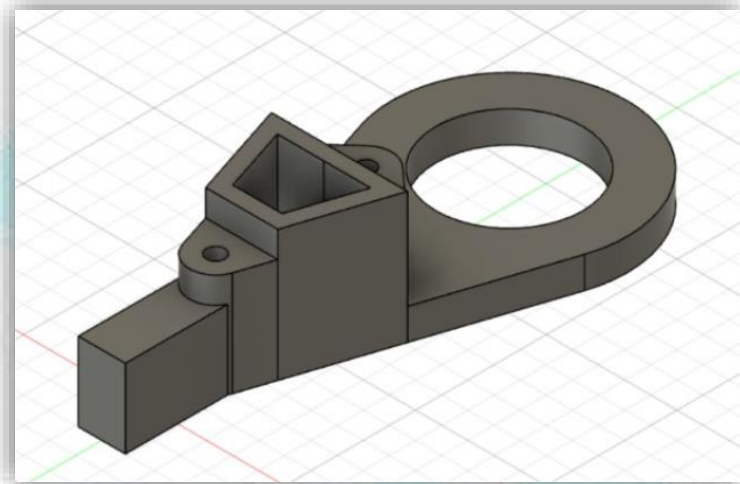
i. The Forearm.

Consider an actual forearm. The gear part is an elbow and connects to the arm. The narrow end connects the wrist. The forearm is to be controlled by one of the smaller NEMA 17 motors.

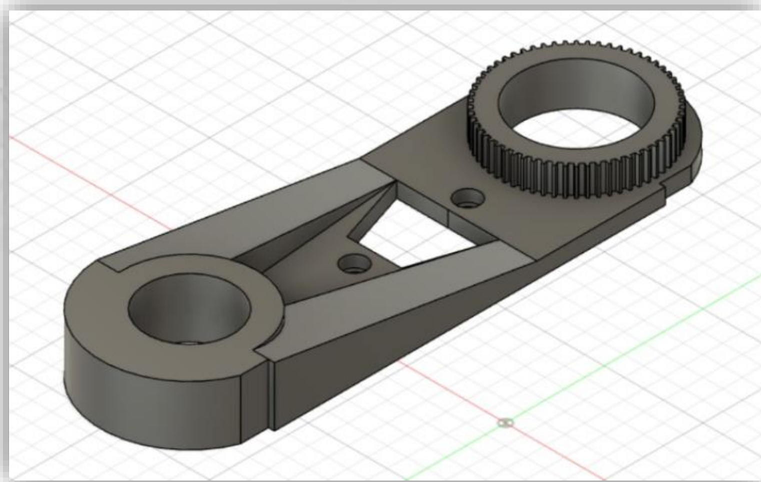


Breaking the arm in two parts:- Lower-upper and Upper-upper arms.

ii. Lower-upper arm.

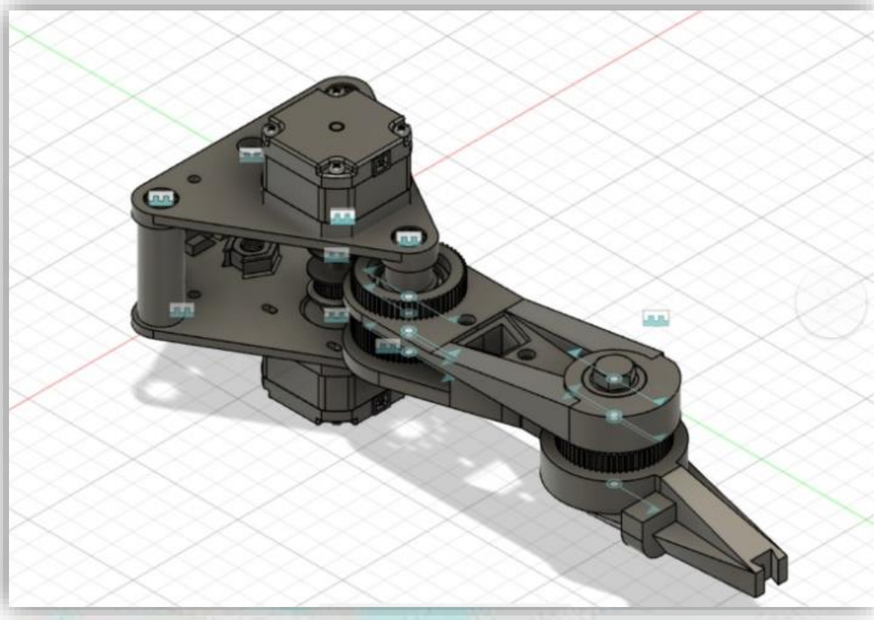


iii. Upper-upper arm.



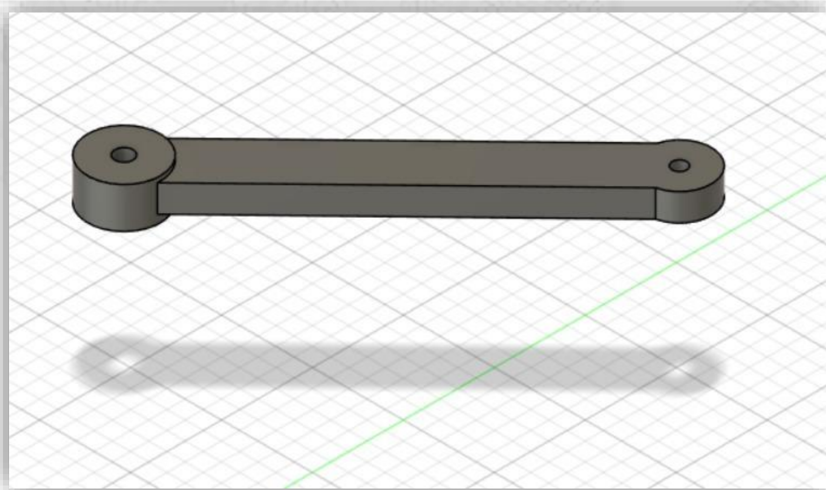
iv. The Z-Carriage.

The Z-Carriage. The whole thing moves along the Z axis. Basically a homing station for all our components.

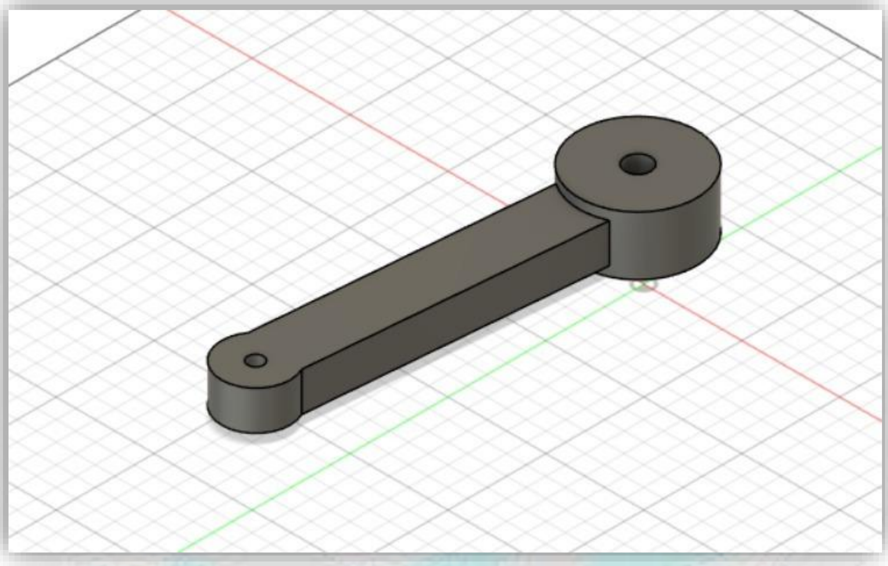


FOR 5-ARM-SCARA →

i. Fore-arm 216mm

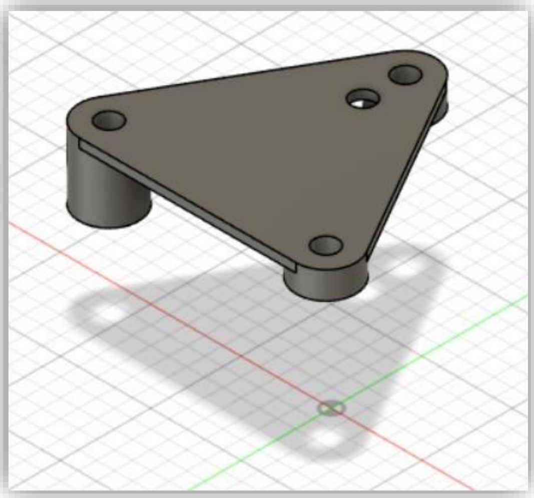


ii. Upper-arm 180mm



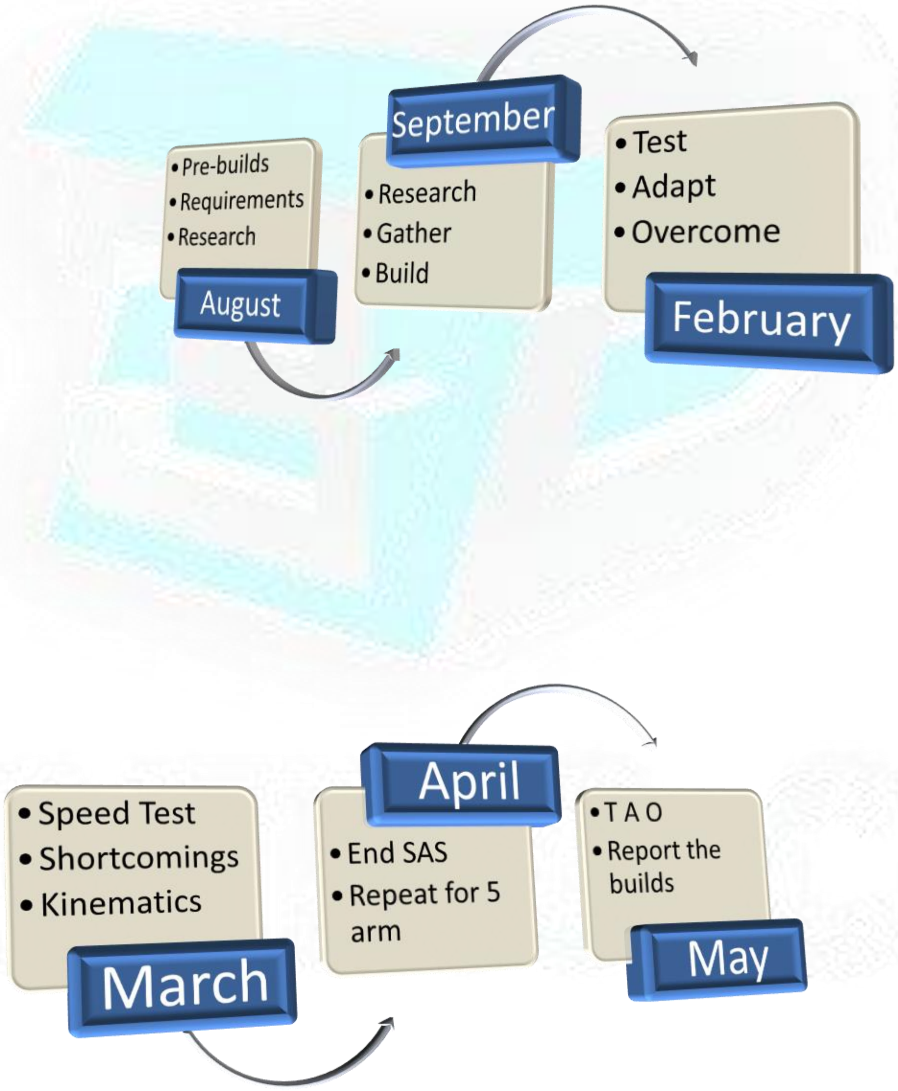
iii. Z-Carriage

A little different. But serves the same purpose of collecting other components



vi. Timeline of work to be done

DISCLAIMER: Owing to COVID-19. There have been some interminable circumstances, such as extension of deadlines.



vii. Acknowledgement

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viii. References, Bibliography

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