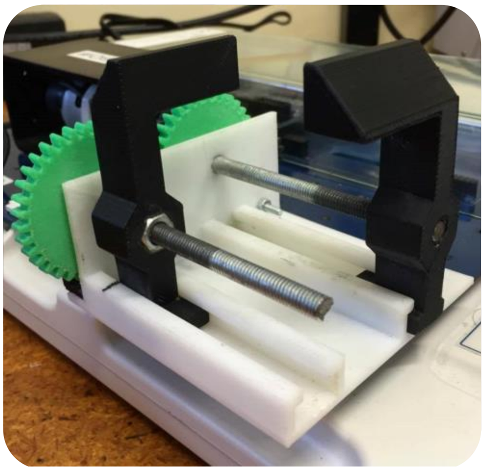
705 Project Report

Robotic Gripper Assignment



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1 Robotic Gripper Mechanical Design

As a part of this project we are tasked to develop a gripper which is driven by the DC Motor using LabVIEW. This gripper needs to be able to grasp an object whose size fits inside the dimensioned box shown in the Figure 1.

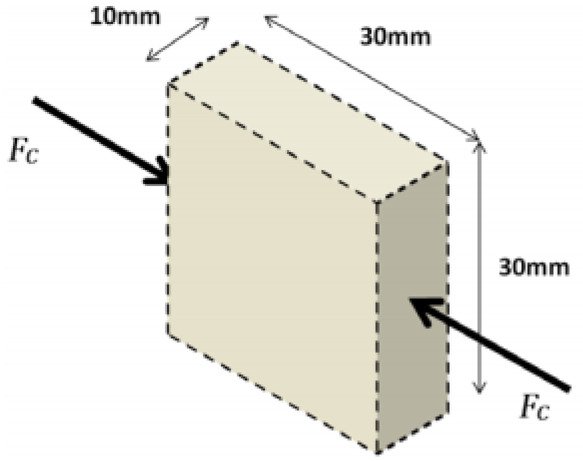


Figure 1 Dimensions of object that needs to gripped

There are many different type of important design considerations that need to be considered to develop the gripper design itself.

- Size of the gripper
- Shape of the gripper, to be able to grip the object in Figure 1
- Mechanical failsafe to protect the equipment and motors from physical damage
- Drive System- linkages/gears/belts
- Gear reduction, required for better control of the gripper

As a part of our design we thought about many different drive systems to power our gripper using the DC motor, such as using a 4 bar linkage or pulley based gripper. These designs would have been complex to manufacture and control using PID in the given time frame.

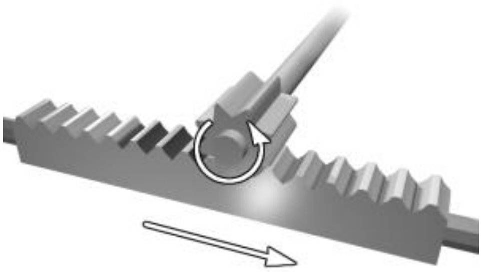


Figure 2 Simple Rack and Pinion

Using a rack and pinion was a simple way of developing the gripper, although if we did use this method there would have not been much of a gear reduction. Another problem we faced using this method was that only one of the arms of the gripper could move if we directly connected it to the motor, doing this we would not be designing a proper gripper. This problems created an interesting design problem as we had to decide how we could power two arms using only one DC motor.

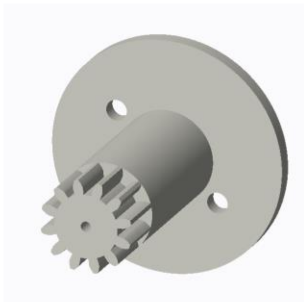


Figure 3 Pinion for DC Motor

Our final design incorporated many different ideas into one design. Instead of using a rack and pinion system, we decided to use a 6mm threaded shaft with a pitch of 1mm to power the arms of the gripper and convert the rotational motion to linear motion e.g. the torque to linear force. Using this type of screw method can amplify the force output, as a small amount of torque on the shaft can exert a large axial force on a load; producing the horizontal sliding movement required for the gripper arms across the bottom mounting plate. The input gear of the gearbox we decided to make had a gear module of 1.3 and 12 teeth. The output gears had the same module and 24 teeth, creating a 1:2 ratio reduction in speed.

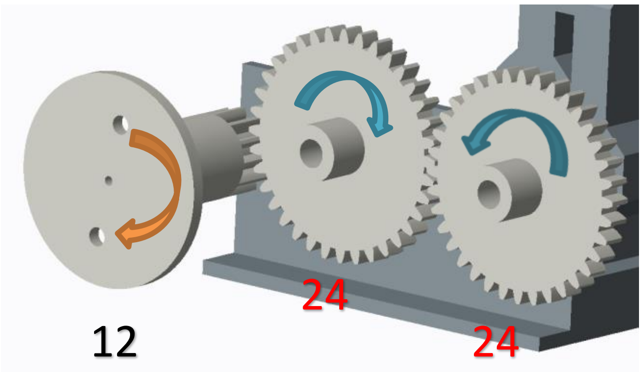


Figure 6 Gears Direction of Movement

We used two spur gears with a 1:1 ratio to generate the rotational motional in opposite directions at the same time, which allowed the gripper arms to close and open depending on the requirement.

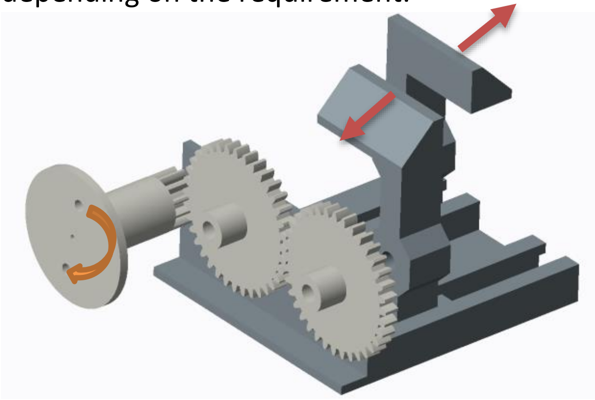


Figure 5 Opening of Gripper Arms

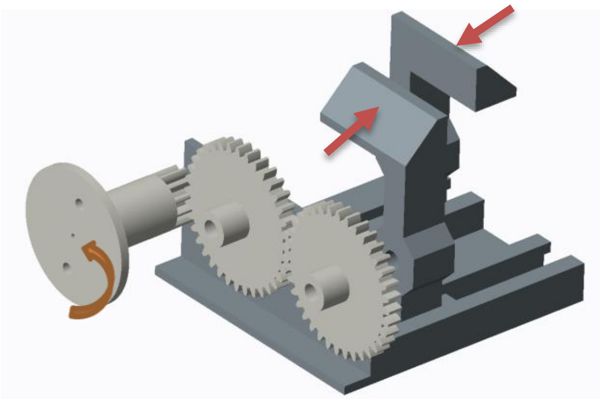


Figure 4 Closing of Gripper Arms

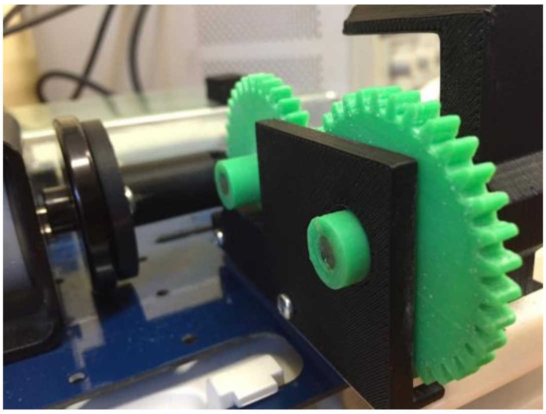


Figure 7 Back Support Plate

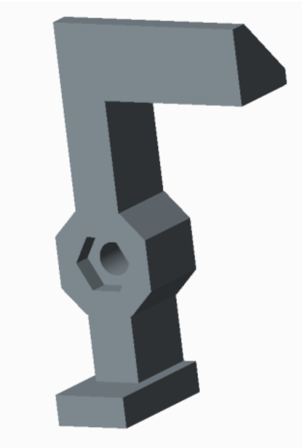


Figure 8 Gripper Arm

The gripper arms are specifically designed to hold a 6mm Hexagon nut which, allows the threaded shaft to screw through the arms and move them linearly. The nuts will be glued on so they don't to come off. The arms come together completely driven by individual threaded shafts, with the flat surface of the arm for gripping. The 6mm shaft will be glued to the gears, so the shaft rotates with the gear. The bottom mounting plate has guide rails for the gripper arms to move along, and also has the mounting holes to attach it to the ELVIS board. A back plate was also designed to keep the gears and position and prevent any unwanted movement. All the parts were printed using the UP! 3D printer, and sanded so all the parts were smooth and fitted perfectly. The mechanical stop for this design is that during the opening of the gripper if one of the arm reaches the end, it stops moving freezing the gripper in position. If the opposite happens the arms close on each other and the gripper freezes, there is not enough force to damage anything.

2 Simulation and Tuning

2.1 Finding Jeq (motor inertia with load connected)

A simulation of the motor without any load connected was created. This simulation was performed using the theoretical disc value of the motor attachment (Jeq of 1.5e-5). (Refer to appendix figure 9).

The motor was then run with the gripper attachment connected to the motor and the angular velocity of the motor was then outputted into a csv file. This angular velocity was graphed using excel (appendix 1 figure 10). In order to determine the correct Jeq of the motor with the load connected, the Jeq in the simulation program was increased until the simulation graph of the angular velocity matched the graph of the real data (ie: appendix 1 figure 10). This resulted in the graph as shown in appendix 1 figure 11. The rising times were then verified for a match using excel and a Jeq of 3.5e-5 resulted in matching rising times.

2.2 Simulating position

The closed loop control for the position is the same model as shown in section 5 for position control. The plant can be modelled as follows:

$$H(s) = \frac{\Omega_m}{V_m} = \frac{K_m}{R_m J_{eq} s + {K_m}^2}$$

The plant model was derived using the equations below:

$$V_m(t) - R_m I_m(t) - E_{emf}(t) = 0 \quad (1)$$

$$E_{emf}(t) = K_m \omega_m(t) \quad (2)$$

$$T_m(t) = J_{eq}\left(\frac{d}{dt}\omega_m(t)\right) \quad (3)$$

$$T_m(t) = K_t I_m(t) \quad (4)$$

Where

Parameter	Description	Units
V_m	Motor terminal voltage	V
R_m	Motor terminal resistance	Ω
I_m	Motor armature current	A
K_t	Motor torque constant	N.m/A
K_m	Motor back-emf constant	V/(rad/s)
ω_m	Angular velocity	Rad/s
T_m	Torque produced by motor	N.m
J_{eq}	Inertia of the motor armature and load	Kg.m^2

Figure 13 in appendix 1 shows the back end implementation of this model (shown in section 5 for position control) in LabVIEW vi. Figure 12 in appendix 1 shows the front end of the position simulation when the desired position is set to 18.5mm (the maximum distance that the rear gripper can move from a set point near the motor end of the track).

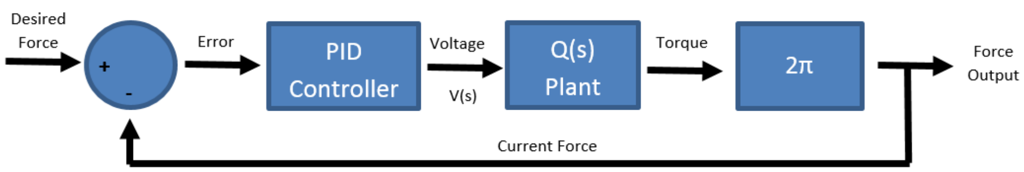
2.3 Finding PID parameters for position

The Ziegler-Nichols Closed-Loop tuning method was used in order to obtain the correct Kp, Ki and Kd parameters. The Ki and Kd parameters were set to 0 and the Kp parameter was increased from 0 until the simulation for the gripper position showed sustained oscillations (i.e.: marginally stable system). This occurred when Kp was set to 8.33. Therefore the model's ultimate gain, Ku is 8.33 and the time period (Tu) of the oscillation, which was found by exporting the oscillated data to excel, was calculated to be 2.08 seconds. Because a classic PID system was chosen, the table shown below was used to calculate the parameters based:

	Kp	Ki	Kd
PID	0.6*Ku	(1.2*Ku)/Tu	0.075*Ku*Tu
PID result	5	0.01	2.08

However, a Ki value was too large to be sensible and when it resulted in large overshoot of the system. Therefore, this was tuned down to give the 0.01 mentioned in the table above.

2.4 Simulating force



The above diagram shows the closed loop control model that was used for the force simulation. Please see appendix 1- figure 17 for derivations of Q(s). Figure 15 in appendix 1 shows the front end UI of force simulation and figure 16 in appendix 1 shows the back end implementation of the above model.

2.5 Finding PID parameters for force

A standard continuous PID vi was used with Kp, Ki and Kd indicators for the PID controller as prescribed by the brief. The Zeigler-Nichols tuning method that was used to find position PID parameters was also used to determine the PID parameters for force. The below table shows these parameters:

	Kp	Ki	Kd
PID result	5	0.01	1.3

3 LabVIEW User Interface

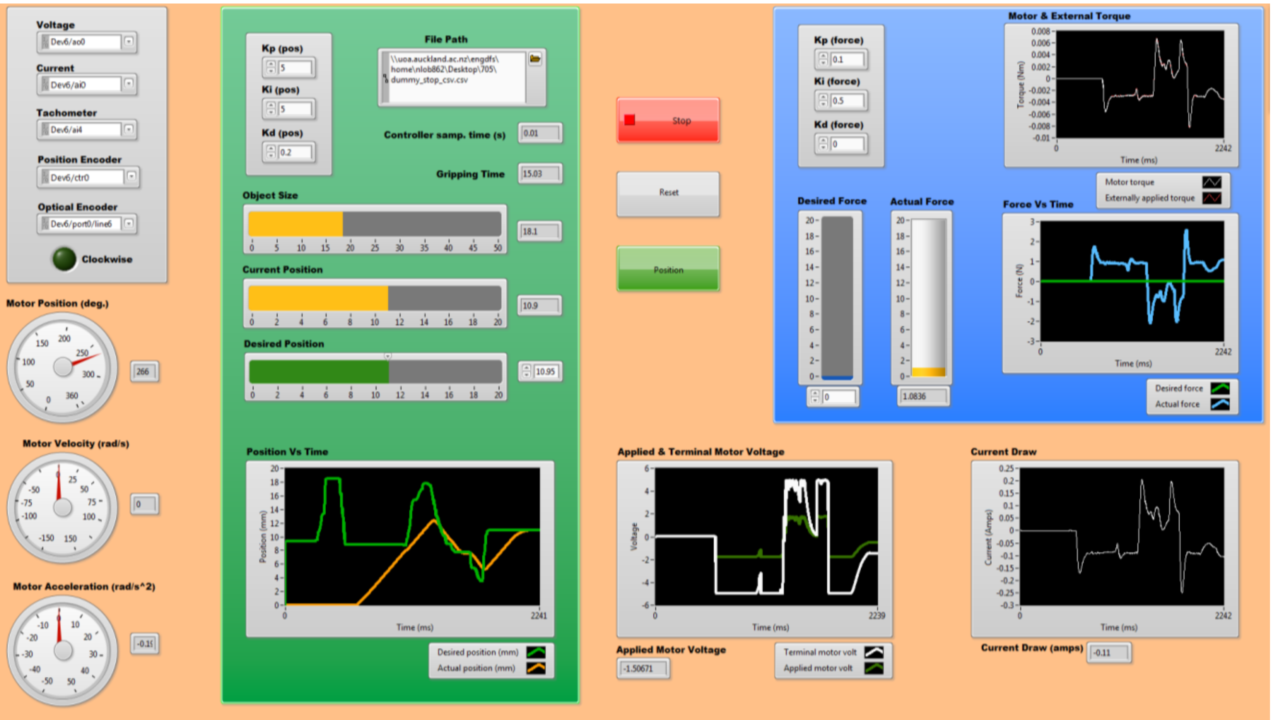


Figure 9 LabVIEW UI Interface

The graphical UI for this LabVIEW program is split into simple easy-to-use sections. All displays in a section are only relevant to controls available in the section which allows for a clean and simple UI.

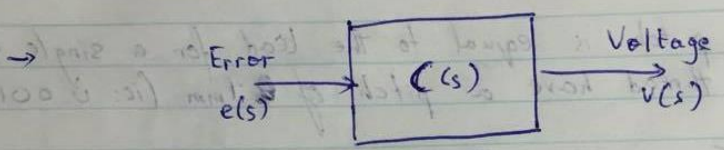
- The Grey box on the left side of the UI allows the user to choose which device to use and change the sensor inputs.
- The meters on the bottom left side displays the motor position (degrees), velocity (rad/s) and acceleration (rad/s^2).
- The Green box contains all the control buttons for Position control. It allows the user to change the PID gains and desired position. It displays the gripper position, the object size, gripping time and graphs the position against time.
- The Blue box contains the controls for Force control. It allows the user to change the PID gains and desired force. It displays the actual force, and graphs the torque and force against time.
- The graphs at the bottom right display the motor voltage and the current drawn by the motor.
- The red Stop button stops the running of the program and sets the motor voltage to zero.
- The yellow reset button returns the gripper back to the initial start position and stops all other control from running until it is turned off.

- The Green button is the switch that allows the user to choose between position and force control, it turns green when position control is turned on and blue when force control is turned on.

4 Digital Controller and Implementation

The below images shows the working for the derivation of the difference equation for the backwards approximation method form the continuous domain to the digital domain. The backwards difference approximation method that was derived in this section was then implemented in a subvi (please refer to appendix 2 – figure 18 and 19).

– Converting continuous PID controller to digital domain using z-transform



$$\rightarrow C(s) = \frac{V(s)}{e(s)} = K_P + \frac{K_I}{s} + K_D s$$

$$= \frac{K_D s^2 + K_P s + K_I}{s} \quad \text{--- (1)}$$

→ This is derived from the control law:

$$u(t) = K_P e(t) + K_I \int_0^t e(\tau)\, d\tau + K_D \frac{d}{dt} e(t)$$

→ Using backward approximation controlled PID:

$$\text{Since } z = e^{sT} = 1 + sT + \frac{(sT)^2}{2!} + \dots$$

and because T is kept small (10 ms) then higher order terms can be ignored.
Therefore z can be approximated by using the first 2 terms in the series:

$$z = 1 + sT$$

But since $z = e^{st}$, it can also be written as $z = \frac{1}{e^{-sT}}$

$$\therefore z = \frac{1}{e^{-sT}} = \frac{1}{1 - sT + \frac{(sT)^2}{2!} + \dots} \approx \frac{1}{1 - sT}$$

$$\therefore s \approx \frac{z - 1}{zT} \quad \text{--- (2)}$$

Substituting (2) into (1) gives:

$$\frac{v(z)}{e(z)} = K_p + \frac{K_I}{\left(\frac{z-1}{zT}\right)} + K_D\left(\frac{z-1}{zT}\right)$$

$$\frac{v(z)}{e(z)} = K_p + \frac{zT}{z-1}K_I + \left(\frac{z-1}{zT}\right)K_D$$

$$\frac{v(z^{-1})}{e(z^{-1})} = K_p + \frac{T}{1-z^{-1}}K_I + \left(\frac{1-z^{-1}}{T}\right)K_D$$

$$(1-z^{-1})\frac{v(z^{-1})}{e(z^{-1})} = (1-z^{-1})K_p + TK_I + (1-z^{-1})(1-z^{-1})K_D$$

$$(1-z^{-1})\frac{v(z^{-1})}{e(z^{-1})} = K_p - K_p z^{-1} + TK_I + (1 - 2z^{-1} + z^{-2})K_D$$

$$(1-z^{-1})v(z^{-1}) = K_p e(z^{-1}) - K_p z^{-1} e(z^{-1}) + TK_I e(z^{-1}) + K_D e(z^{-1}) - 2K_D z^{-1} e(z^{-1}) + K_D z^{-2} e(z^{-1})$$

$$v(z^{-1}) - z^{-1}v(z^{-1}) = K_p e(z^{-1}) - K_p z^{-1} e(z^{-1}) + TK_I e(z^{-1}) + K_D e(z^{-1}) - 2K_D z^{-1} e(z^{-1}) + K_D z^{-2} e(z^{-1})$$

Since $v(z^{-1}) = v(k)$, $z^{-1}v(z^{-1}) = v(k-1)$
and $e(z^{-1}) = e(k)$, $z^{-1}e(z^{-1}) = e(k-1)$, $z^{-2}e(z^{-1}) = e(k-2)$

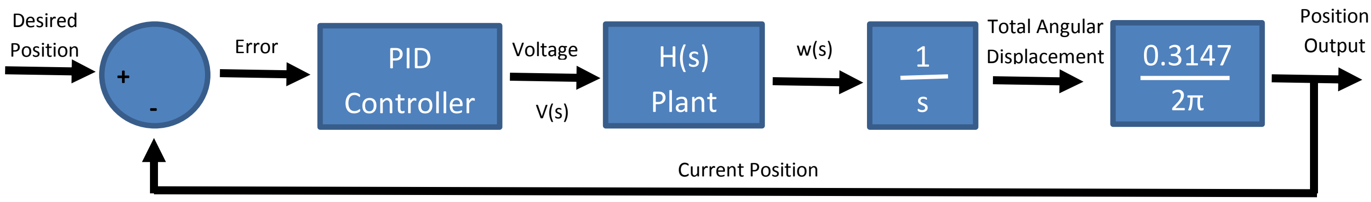
Then therefore:

$$v(k) - v(k-1) = K_p e(k) - K_p e(k-1) + TK_I e(k) + K_D e(k) - 2K_D e(k-1) + K_D e(k-2)$$

$$\therefore v(k) = v(k-1) + K_p e(k) - K_p e(k-1) + TK_I e(k) + K_D e(k) - 2K_D e(k-1) + K_D e(k-2)$$

$$= v(k-1) + e(k)\left[K_p + TK_I + K_D\right] - e(k-1)\left[K_p + 2K_D\right] + K_D e(k-2)$$

5 Position Control



To implement position control, first we had to figure out how to measure the rotational position of the DC motor in degrees. We connected the motor encoder to our program and figured out how many ticks it took for the motor to make one full rotation. This was done 6 times in both clockwise and anticlockwise directions to get full accuracy. After taking the measurements we found it took 4093 ticks to complete a full turn, 11.37 ticks per degree. From this information we could figure out the angular position of the motor and find out where it was positioned.

From the angular position and direction encoder we could figure out the number of turns the motor had made, which we could then use to calculate our gripper position. We then connected our gripper mechanism and tried to find out the linear position change of the gripper arms with each turn. 5 measurements were made, and the number of turns and distance travelled were recorded. From this we calculated that the gripper arms moved 0.3147mm every full turn of the motor.

Converting to Average Ticks per Motor Turns

	Number of Turns	Ticks	Ticks/turn
1	10	40937	4093.7
2	10	40920	4092
3	-10	-40986	4098.6
4	-10	-40963	4096.3
5	20	81731	4086.55
6	-20	-81819	4090.95
	Average Ticks/turn		4093.016667
	Ticks per degree		11.36949074

After we figured the linear position we could then implement our Digital PID controller (subvi – appendix 2 figure 18 and 19). We feed the desired position into the controller, which then figures out the voltage to be applied and adjusts it according to the error in the gripper arms current position. From this the PID gain values we used in section 2.3 gave us minimal overshoot and nearly negligible oscillation but the parameters had to be adjusted in order to overcome the extra friction of our system. Ki had to be increased to eliminate steady state error and Kd had to be decreased to decrease unstable fluctuations. This gave us the following final PID values for position:

Converting Number of Turns to mm per Motor Turn

	Turns	Distance (mm)	mm/turn
1	50.53	16	0.31664358
2	41.79	13	0.31107921
3	48.86	15.5	0.31723291
4	44.05	14	0.31782066
5	49.91	15.5	0.31055901
		Average mm/turn	0.31466707

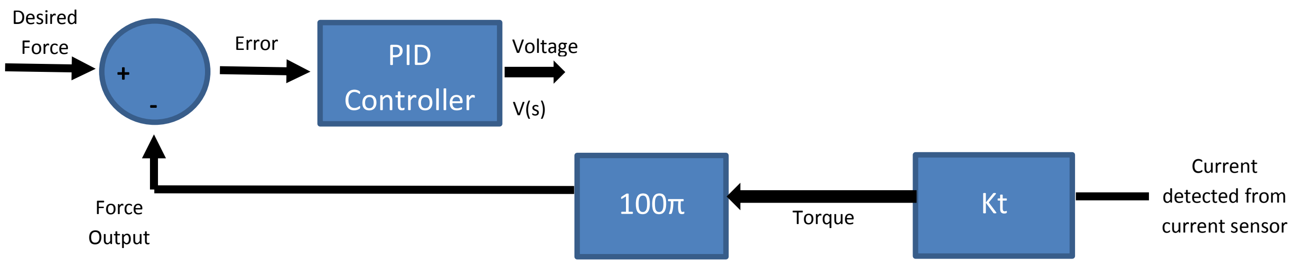
	Kp	Ki	Kd
PID result	5	5	0.2

From the gripper position we can figure out what the size of the object being gripped is. We know what the maximum gripper separation is and from that we minus the current position to give us the objects size.

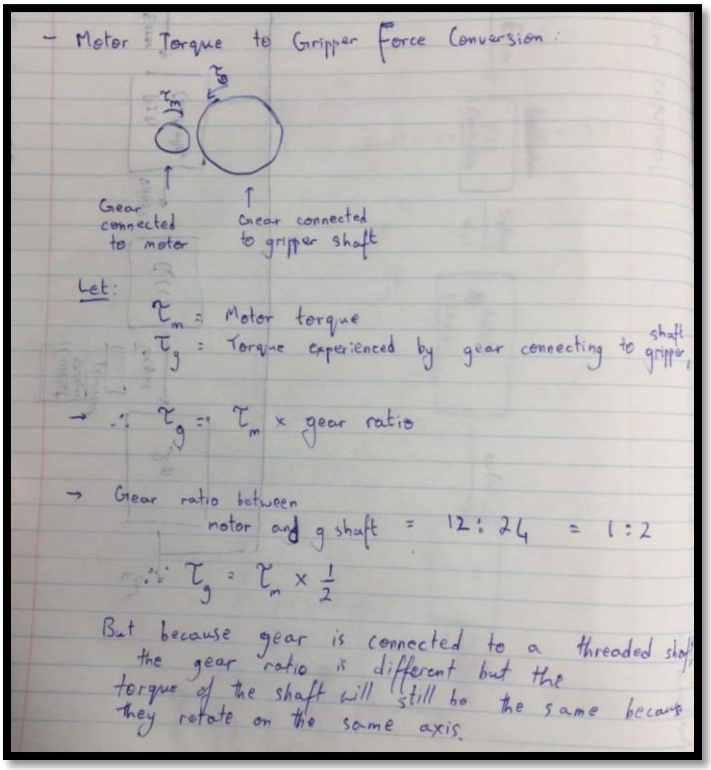
The final implementation of the position control is shown by appendix 2 – figures 20 and 21.

6 Force Control

Unlike our simulation our force control is not a closed loop (as shown by below control diagram) because it uses the current sensor to detect the current, from which a torque and finally the force is calculated.



Our motor torque to gripper force conversion can be expressed as F = (T * 2* pi) /l, where l is lead which is equal to the pitch for a single start screw. Since we used a single thread M6 screw as our shaft for the gripper arms, l was 0.01 and the gear ratios meant that the total torque to force conversion ratio was 100*pi. The below image shows our working for the torque to force conversion and the calculation for the maximum force that can be exerted by the gripper.



$$\therefore F_{out} = \frac{2\pi}{l} \times T_{in}$$

where l is the lead of the threaded shaft.
The pitch is equal to the lead for a single start screw. Therefore lead is 0.01m

$$\therefore F_{out} = \frac{2\pi}{0.01} \times T_{into\ shaft}$$

$$\therefore F_{gripper} = 200\pi \times T_{motor} \times \frac{1}{2}$$

$$= 100 \times T_m \times \pi$$

$$= 100 \times K_T \times I_m \times \pi$$

I_{max} was found to be 1.39 Amps and K_T was 0.032768

$\therefore$ Maximum force of gripper is

$$F_{gripper\ max} = 100 \times 0.0327 \times 1.39 \times \pi$$
$$= 14.3\ N$$

Therefore the control for the force was implemented exactly by the open loop control model shown on the previous page. The PID subvi which was developed in section 4 (also see appendix 2 figure 18 and 19) was used for the force control to covert the error into a voltage. The final implementation of the force control can be seen in appendix 2 figures 22 and 23. The PID parameters that were developed in section 2.4 resulted in slow rising times and large overshoot, therefore it had to be fine-tuned by a combination of Ziegler Nichols tuning method and the table shown below:

	Rise Time	Overshoot	Settling Time	Steady-State Error
Increase in Kp	Decreases	Increases	~	Decreases
Increase in Ki	Decreases	Increases	Increases	Eliminated
Increase in Kd	~	Decreases	Decreases	~

This resulted in the final PID values shown below:

	Kp	Ki	Kd
PID result	0.1	0.5	0

7 Appendix 1 - Simulation

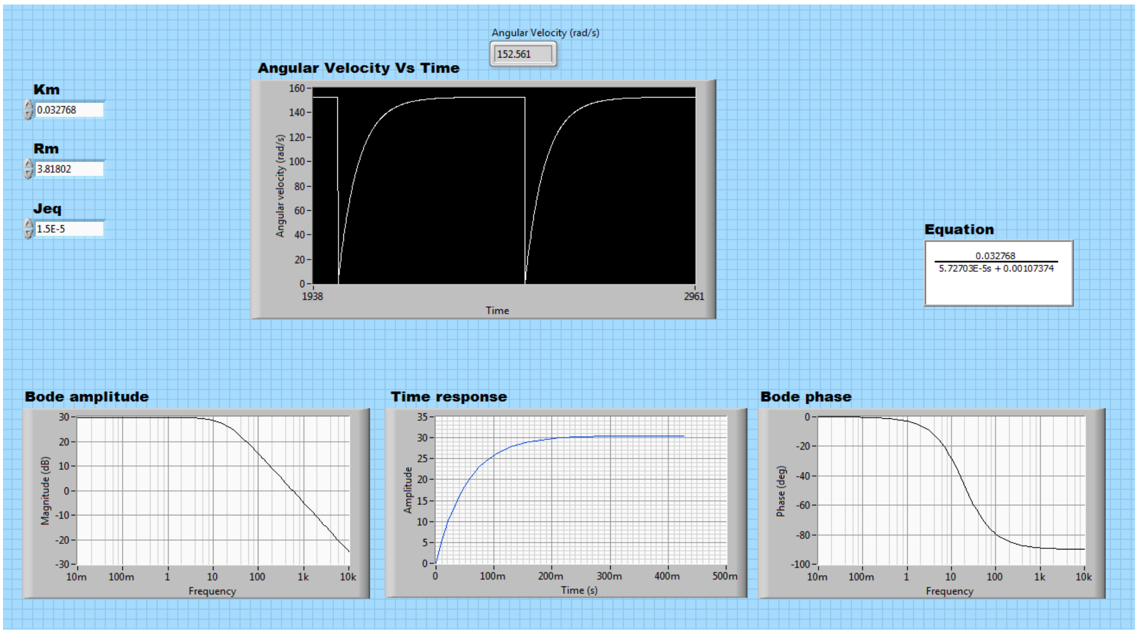


Figure 10 Simulation of the motor without connecting any load to it

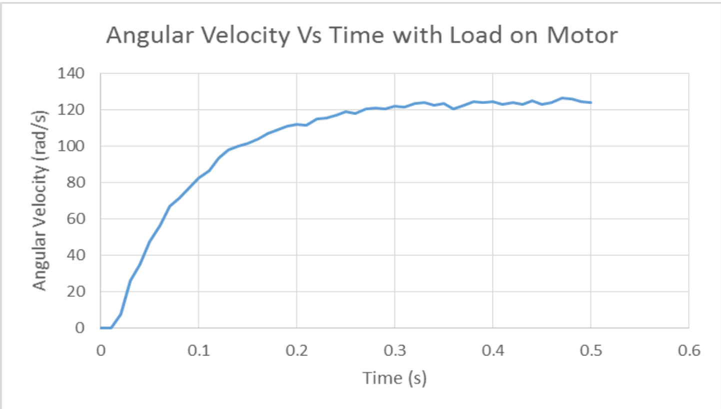


Figure 11 Results when the motor is run with the gripper attachment connected

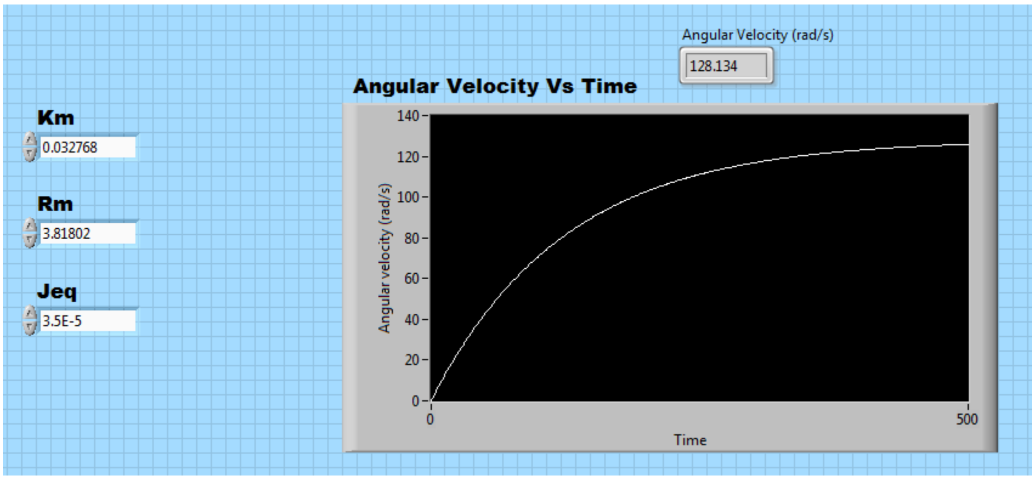


Figure 12 showing a Jeq of 3.5e-5 resulting in a matching curve to real data

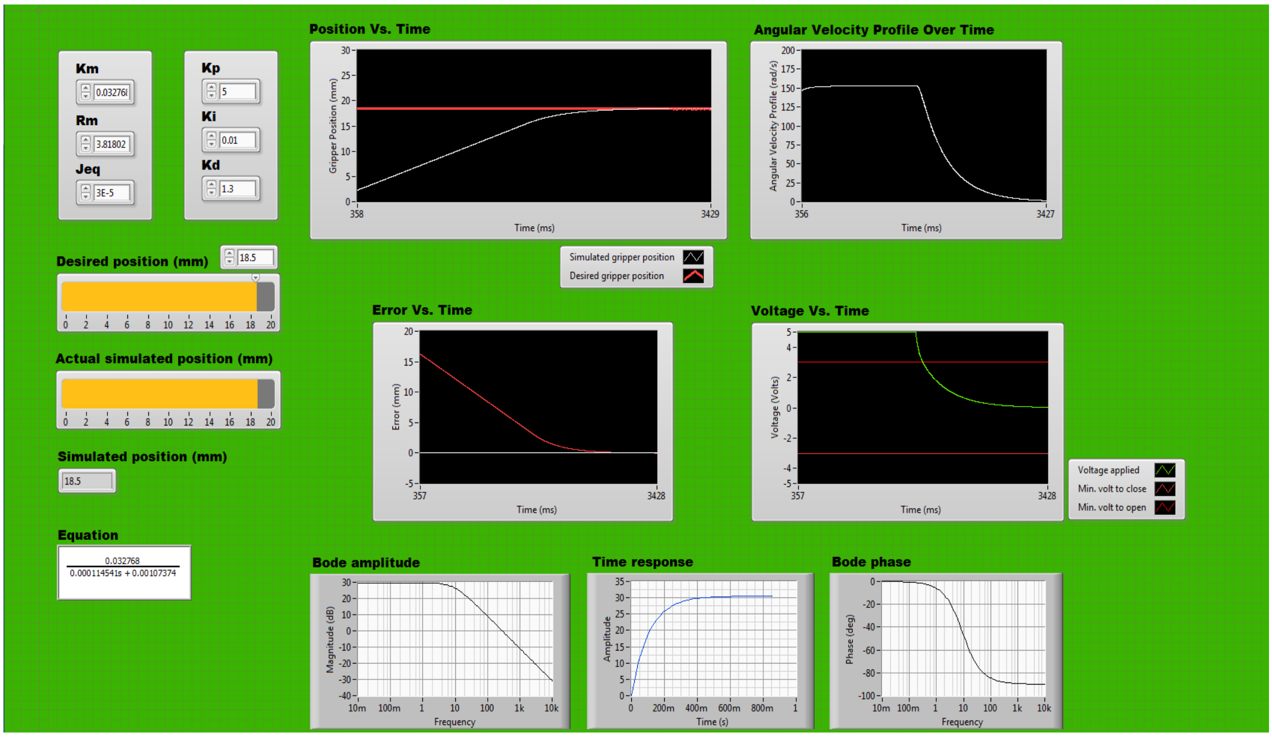


Figure 13 showing front end UI of position simulation

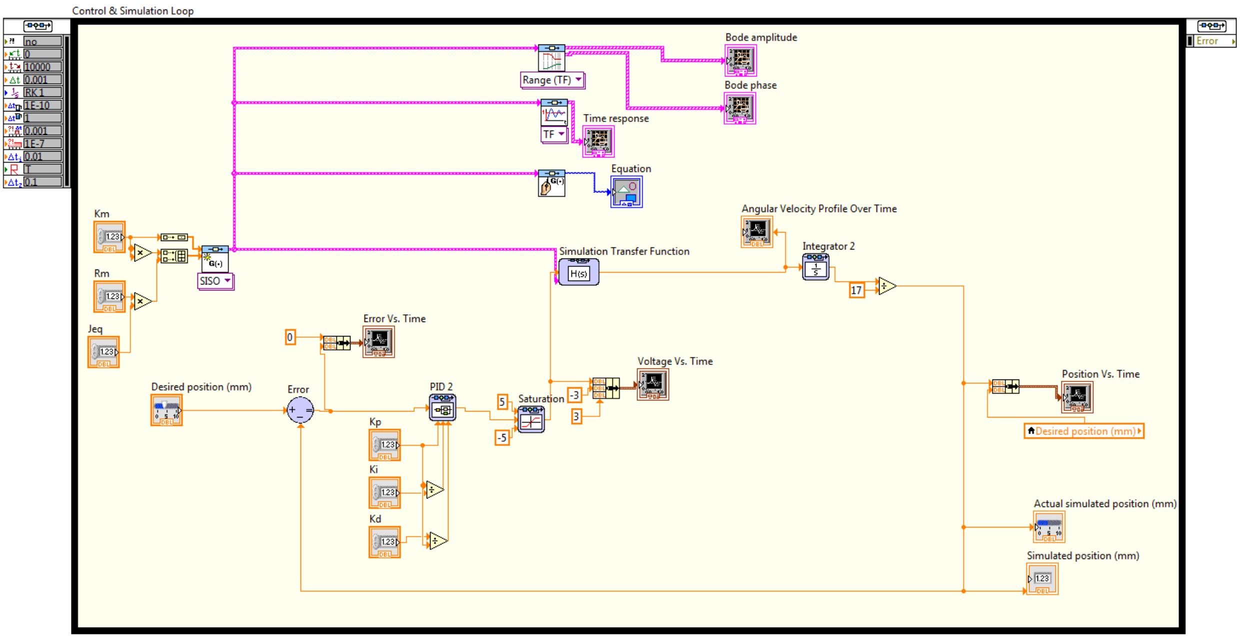


Figure 14 showing back end implementation of position simulation

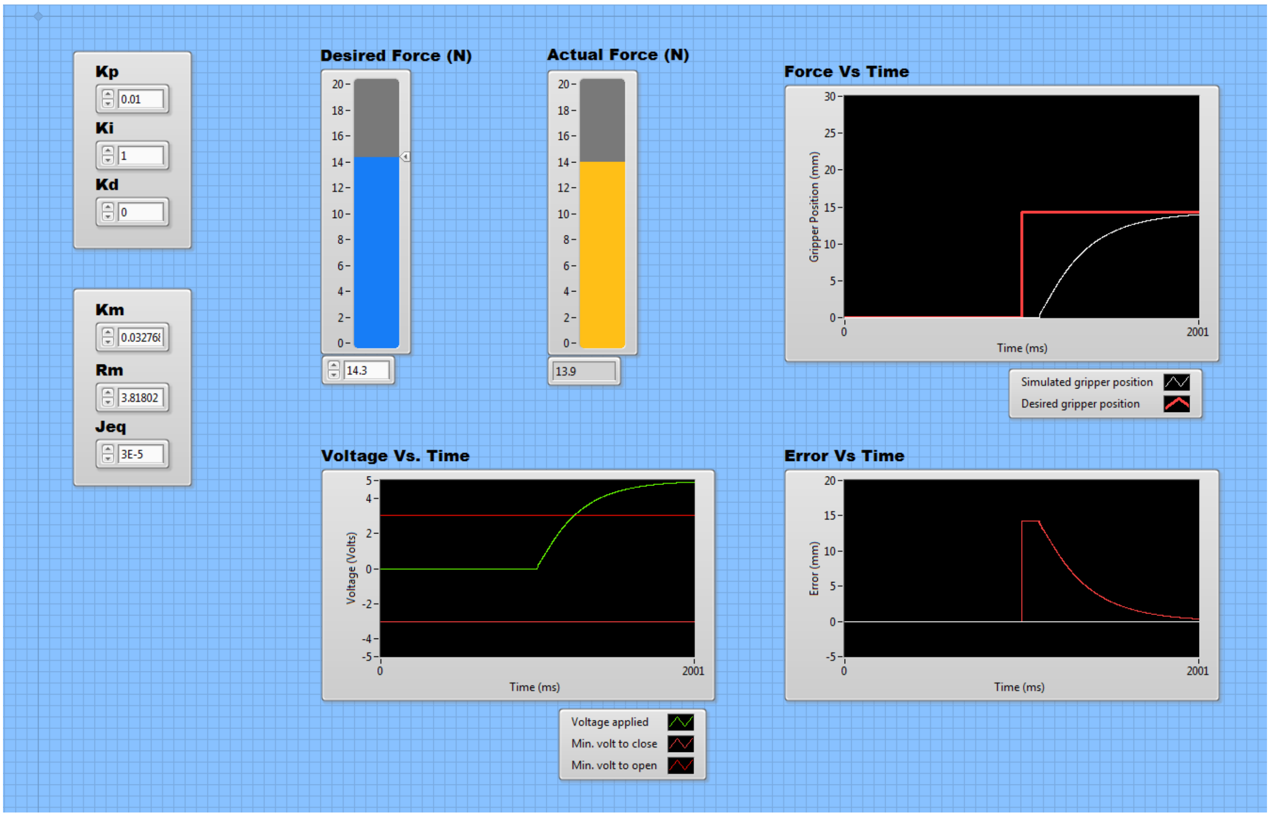


Figure 15 showing front end UI of force simulation

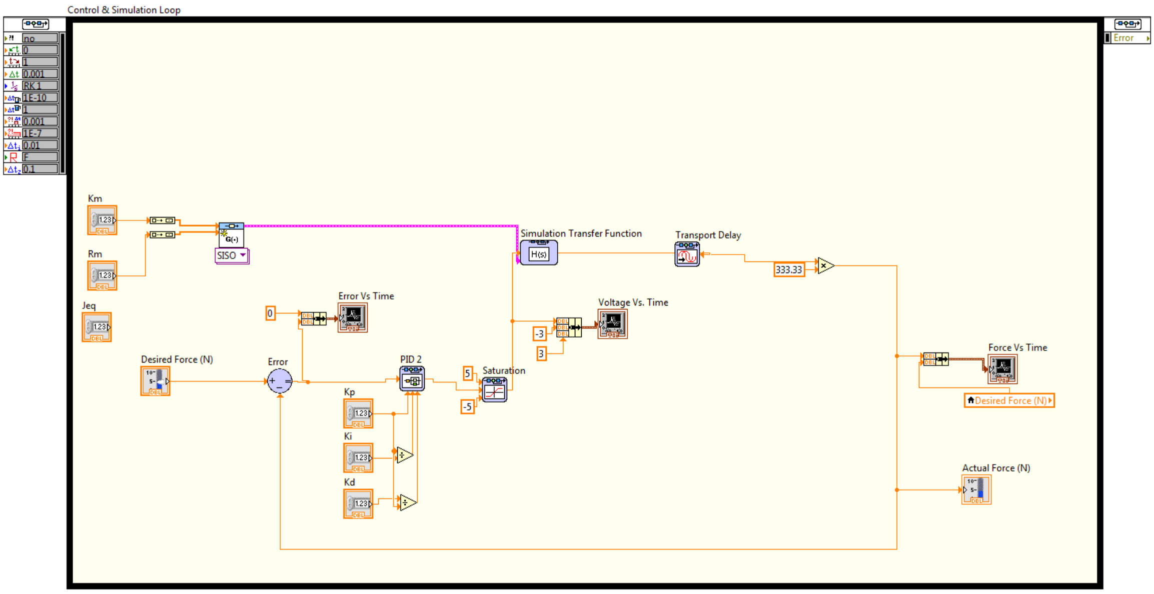


Figure 16 showing back end implementation of force simulation

Force Simulation

→ $V_m(t) - R_m I_m(t) - E_{emf}(t) = 0$ (1)

$E_{emf}(t) = K_m \omega(t)$ (2)

$T_m(t) = K_t I_m(t)$ (3)

→ When object is being gripped, speed of the motor is zero which means that equation (2):

$$E_{emf}(t) = 0 \quad (4)$$

→ Substitute (4) into (1):

$$V_m(t) - R_m I_m(t) = 0$$

$$\therefore V_m = I_m R_m$$

$$I_m = \frac{V_m}{R_m} \quad (5)$$

→ Substitute (5) into (3)

$$T_m(t) = K_t \times \frac{V_m(t)}{R_m} \quad (6)$$

→ Laplace of (6):

$$\mathcal{L}\{T_m(t)\} = \mathcal{L}\left\{K_T \times \frac{V(t)}{R_m}\right\}$$

$$\frac{T(s)}{V(s)} = \frac{K_T}{R_m}$$

Figure 17 showing working and equations to derive the model that converts voltage to torque

8 Appendix 2

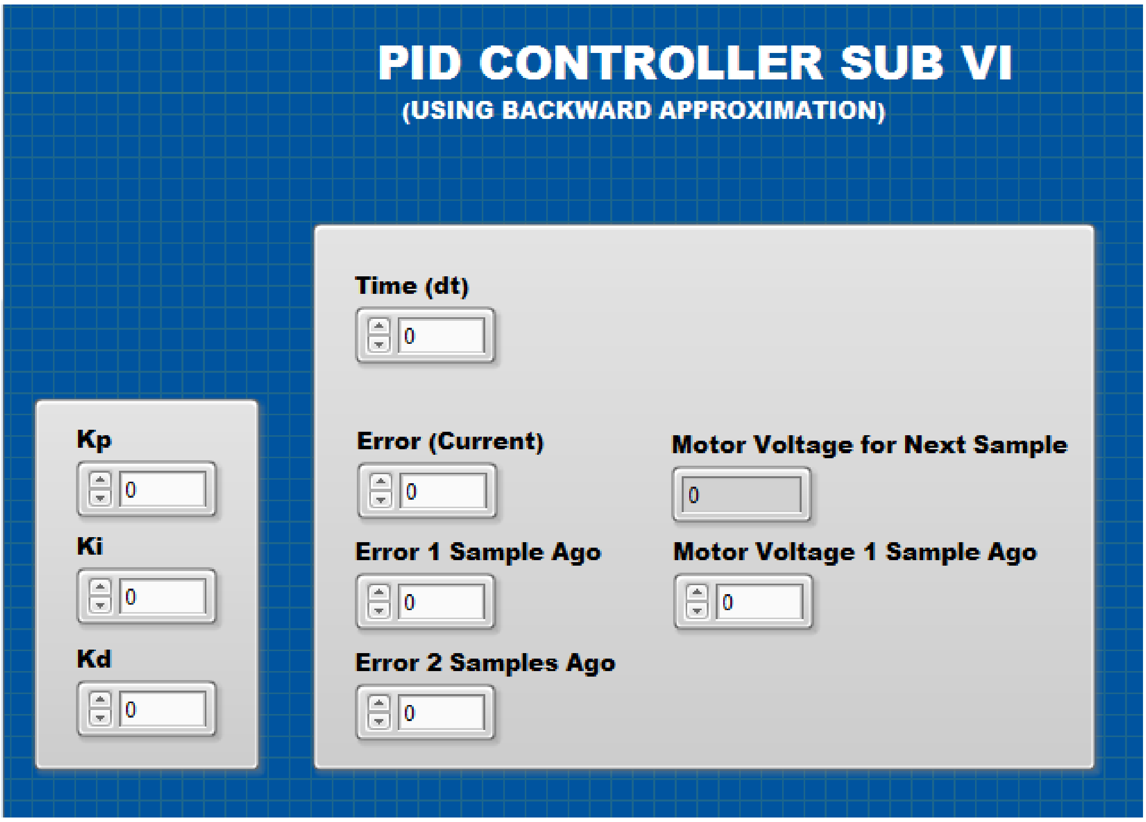


Figure 18 showing PID controller subvi

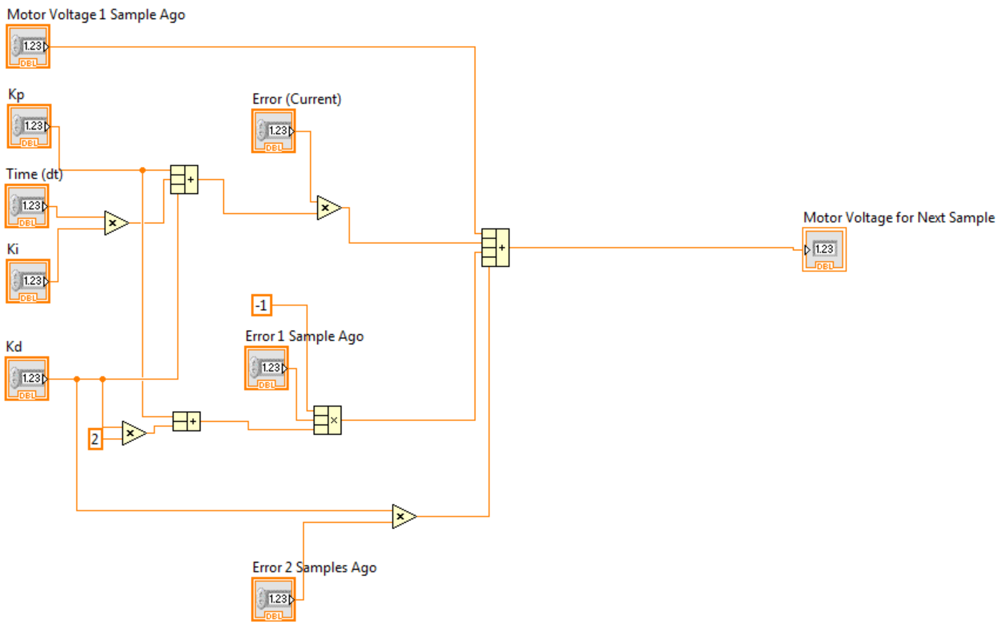


Figure 19 showing the implementation of the backwards approximation of PID

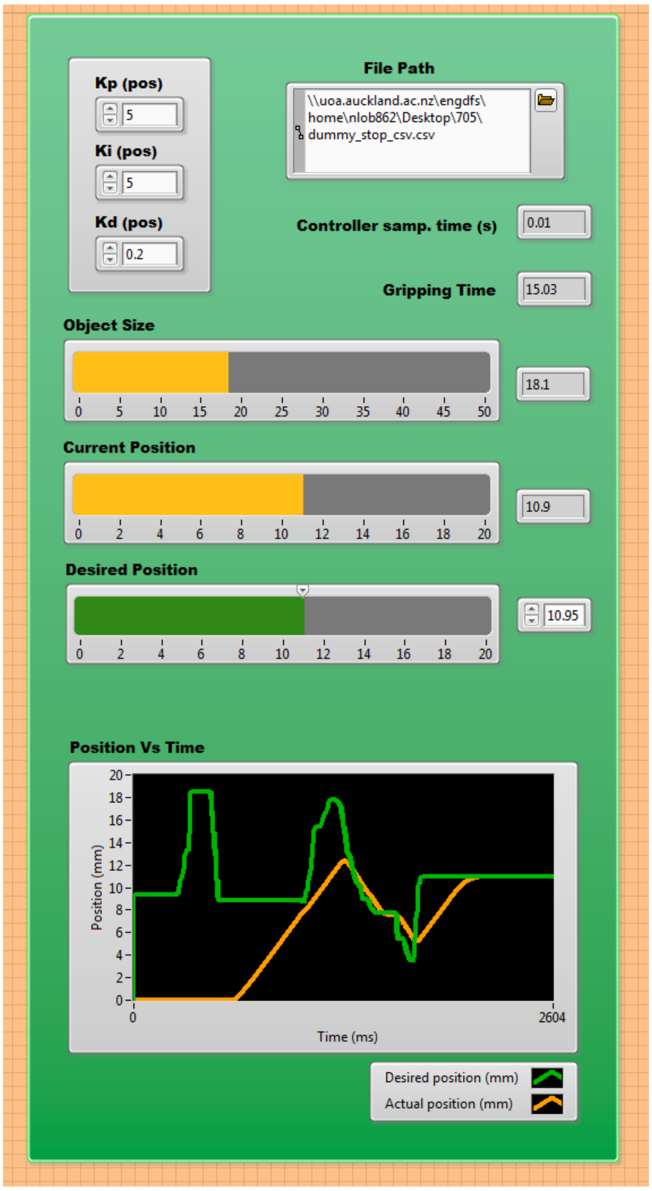


Figure 20 showing UI for position control

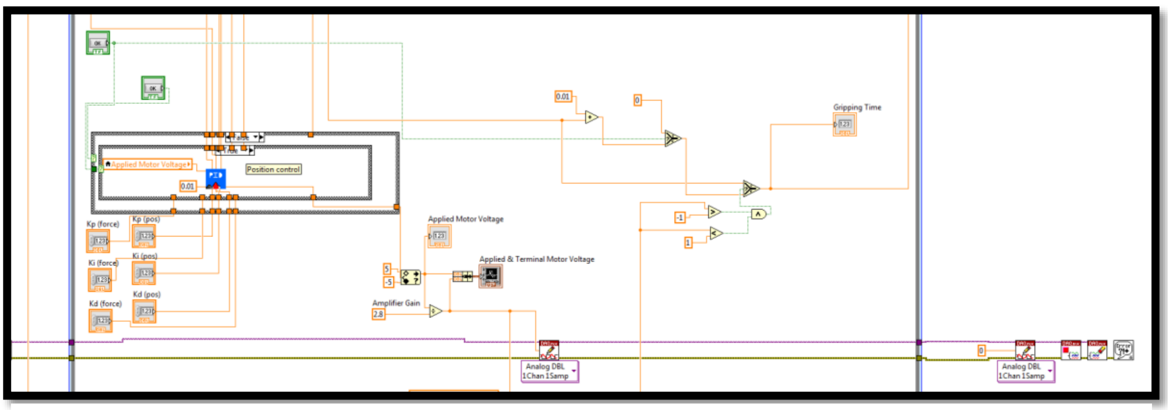


Figure 21 showing back end implementation of position control

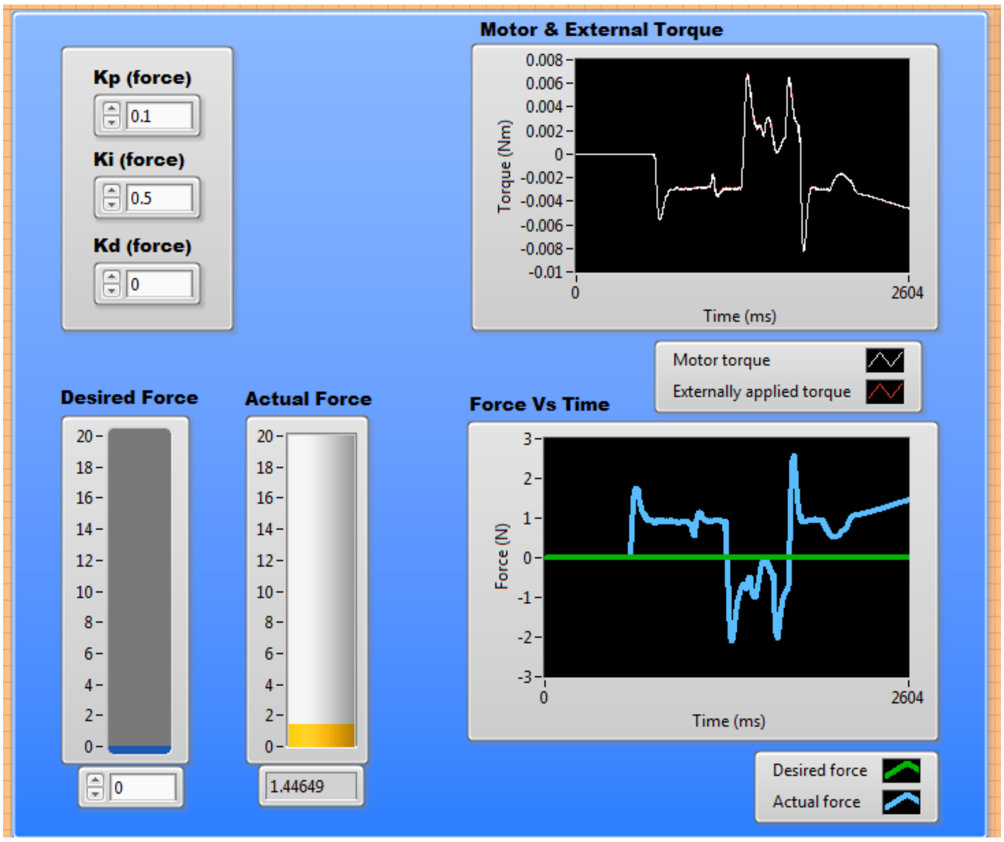


Figure 22 showing UI for force control

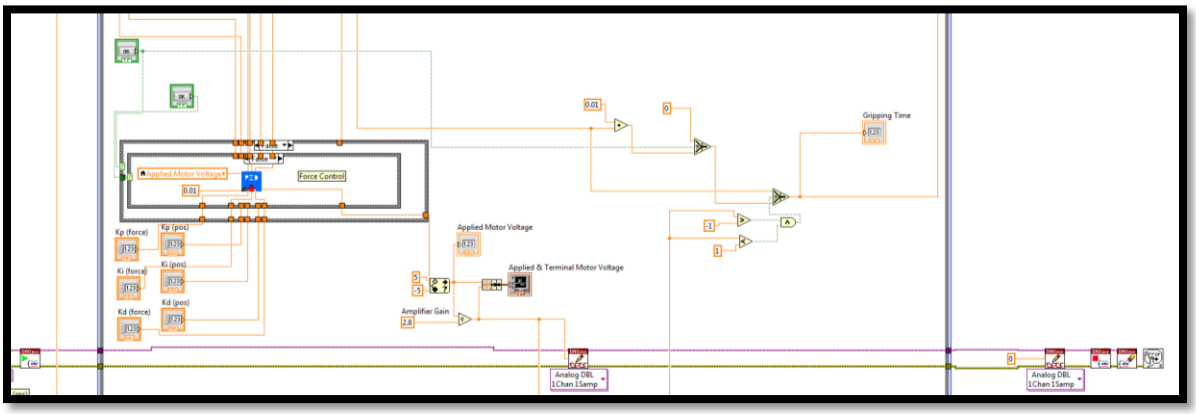
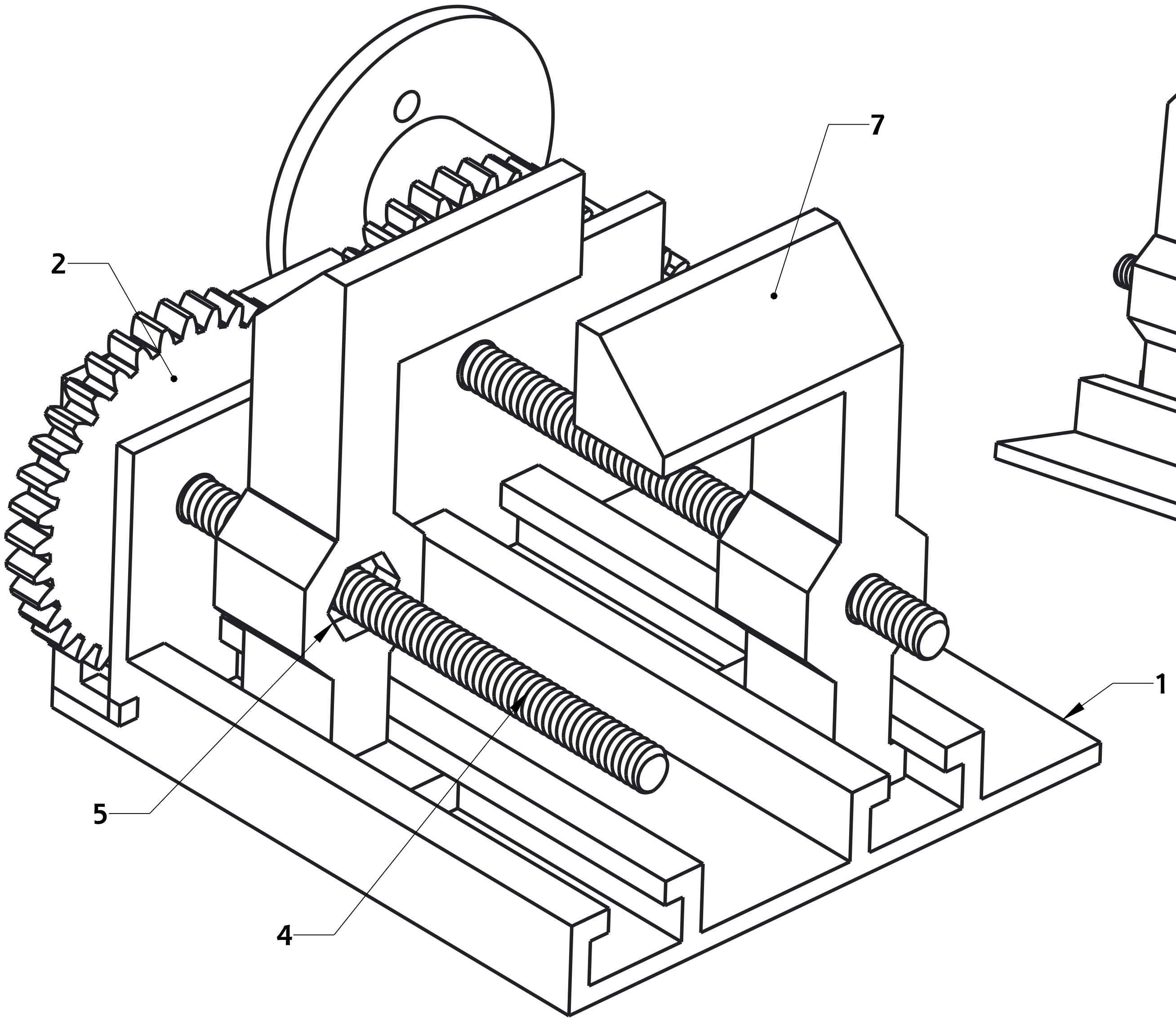


Figure 23 showing back end implementation of force control

9 Appendix 3 – Mechanical drawings



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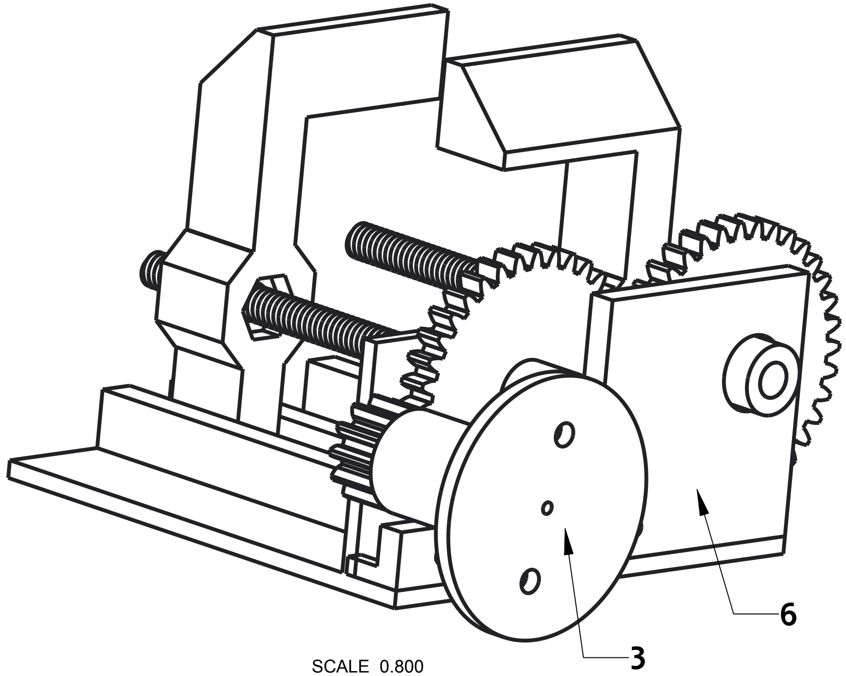


SCALE 0.800

Part No.	Name of Part	Qty.	Material
1	**Mounting Plate**	1	**ABS**
2	**Large Gear**	2	**ABS**
3	**Pinion**	1	**ABS**
4	**10 cm Threaded Shaft 6mm**	2	**Stainless Steel**
5	**Nut M6**	2	**Stainless Steel**
6	**Back Plate**	1	**ABS**
7	**Gripper Arm**	2	**ABS**

Change No.	Name of Item	Changes Made	OK	Date

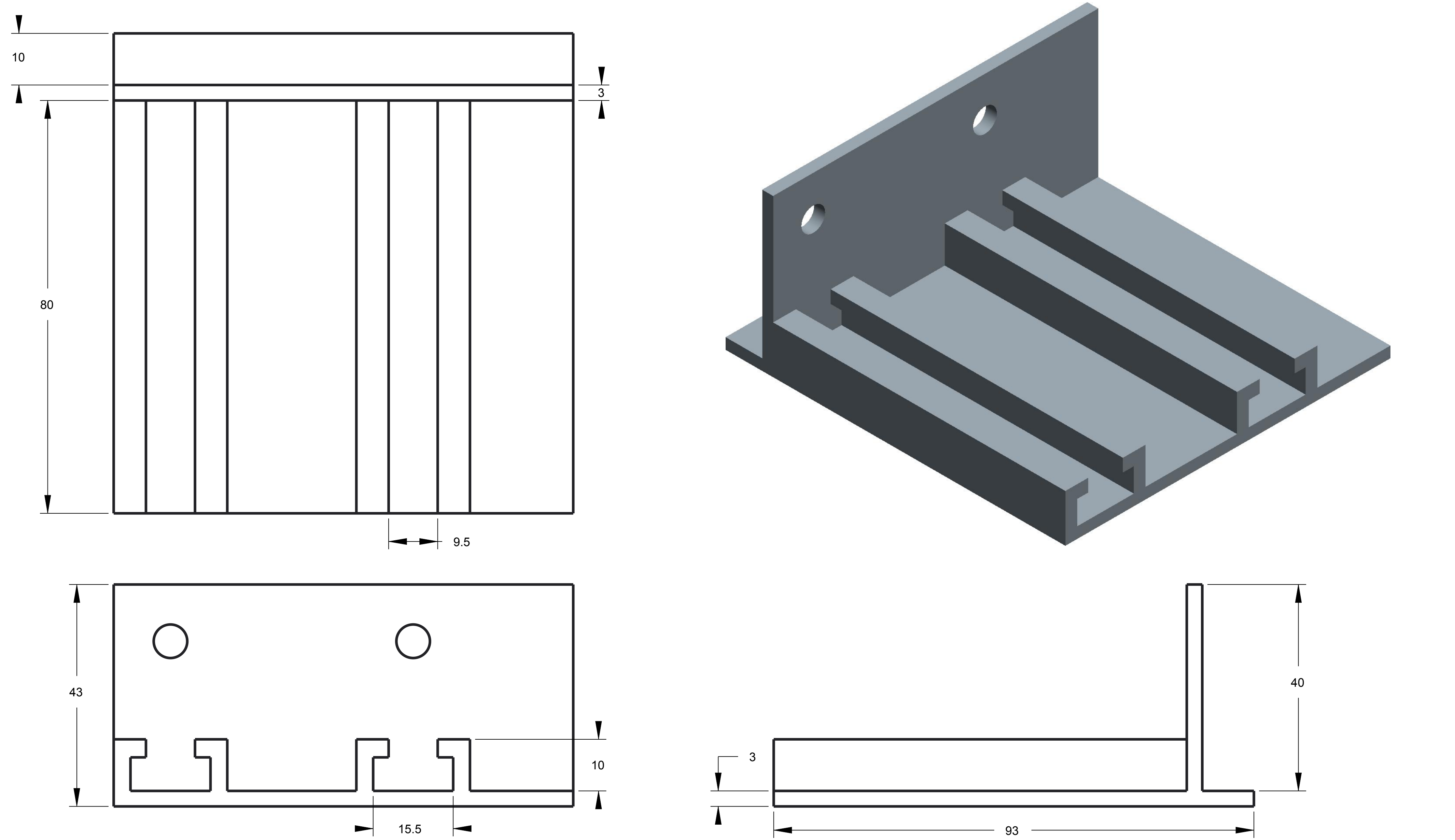
THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

DRAWN BY	**Manmeet Singh & Nitish Lobo**
TUTOR	
GROUP No.	
FILENAME	
DATE	

TITLE	Gripper Assembly
DEPARTMENT	Mechanical Engineering
FILE LOCATION	
QUANTITY	1
SCALE	1 : 1
SHEET	1 of 1
	A4

ALL TOLERANCES ARE ±0.1mm UNLESS OTHERWISE SPECIFIED

ALL DIMENSIONS IN MILLIMETRES



					DRAWN BY Manmeet Singh & Nitish Lobo	TITLE Mounting Plate with Sliders
					TUTOR	DEPARTMENT Mechanical Engineering
					GROUP No.	
Change No.	Name of Item	Changes Made	OK	Date	FILENAME	FILE LOCATION
ALL TOLERANCES ARE ±0.1mm UNLESS OTHERWISE SPECIFIED		ALL DIMENSIONS IN MILLIMETRES			DATE	MATERIAL — Qty. 1 — SCALE 1 : 1 — SHEET 1 of 1 — A4

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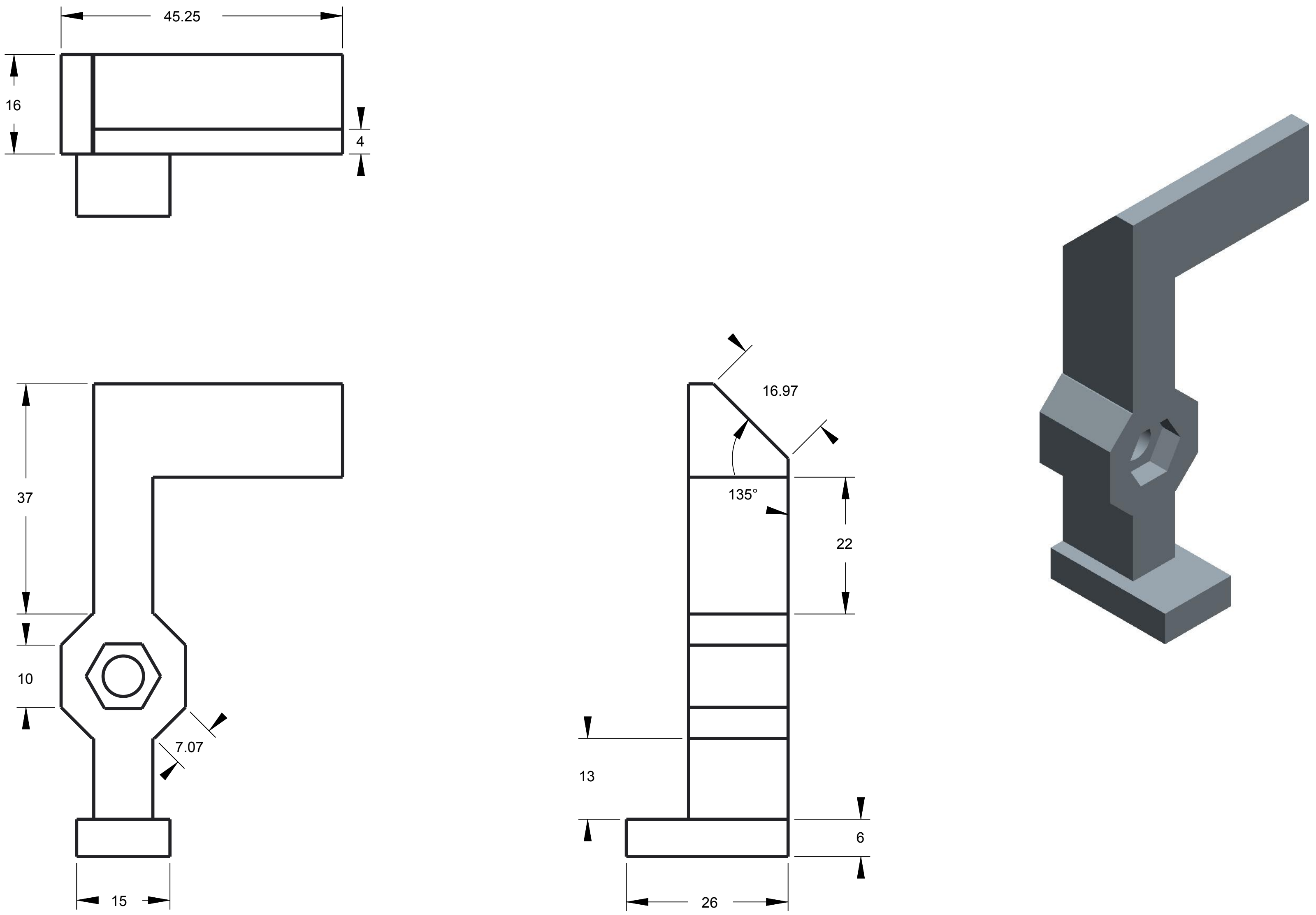

Change No.	Name of Item	Changes Made	OK	Date

THE UNIVERSITY OF AUCKLAND
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NEW ZEALAND

DRAWN BY **Manmeet Singh & Nitish Lobo**

TUTOR

GROUP No.

FILENAME

DATE

TITLE Gripper Arm

DEPARTMENT Mechanical Engineering

FILE LOCATION

MATERIAL

Qty. 1

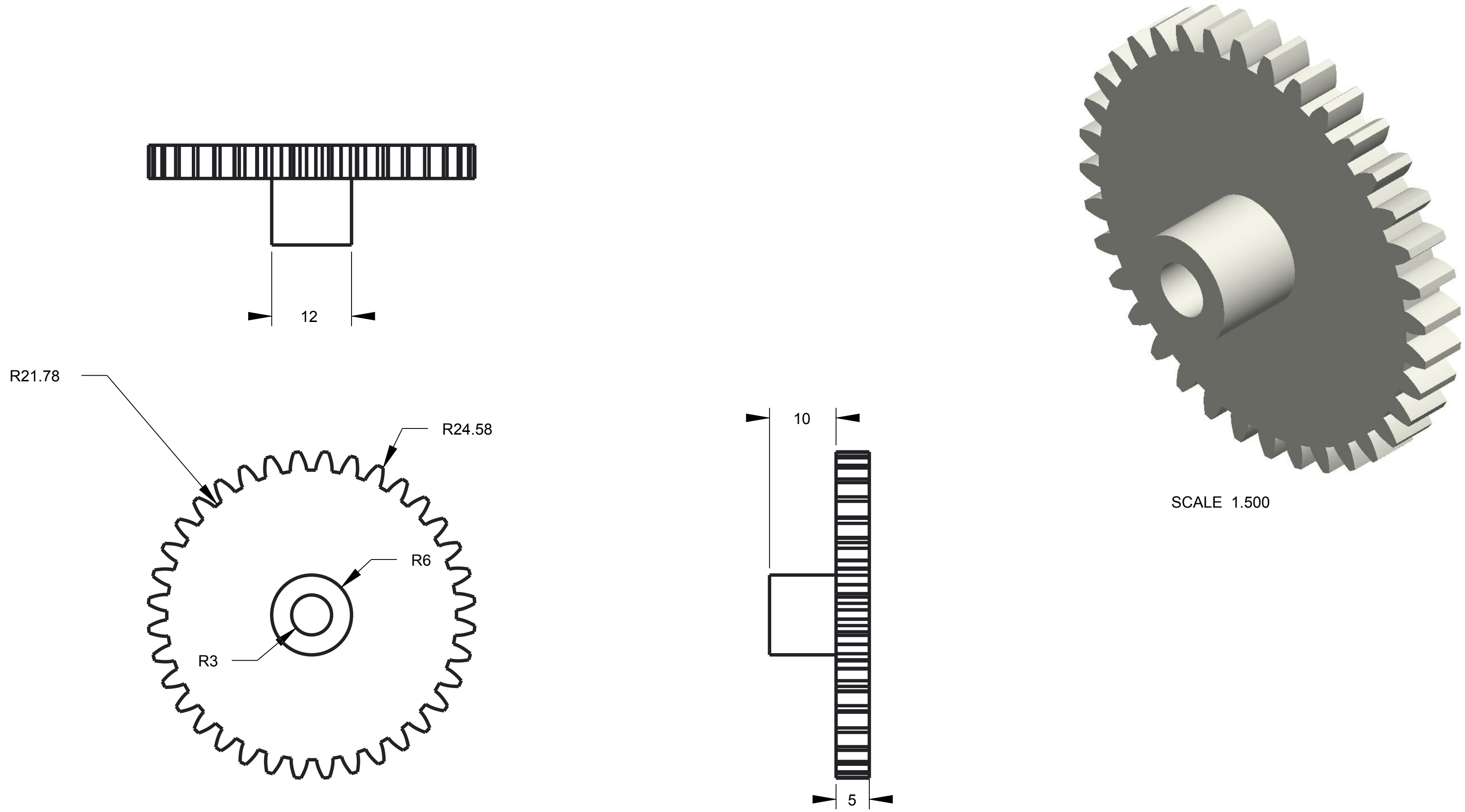
SCALE 1 : 1

SHEET 1 of 1

A4

ALL TOLERANCES ARE ±0.1mm UNLESS OTHERWISE SPECIFIED

ALL DIMENSIONS IN MILLIMETRES



Change No.	Name of Item	Changes Made	OK	Date

THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

DRAWN BY **Manmeet Singh & Nitish Lobo**

TITLE Large Gear

TUTOR

DEPARTMENT Mechanical Engineering

GROUP No.

FILENAME

FILE LOCATION

ALL TOLERANCES ARE ±0.1mm UNLESS OTHERWISE SPECIFIED

ALL DIMENSIONS IN MILLIMETRES

DATE

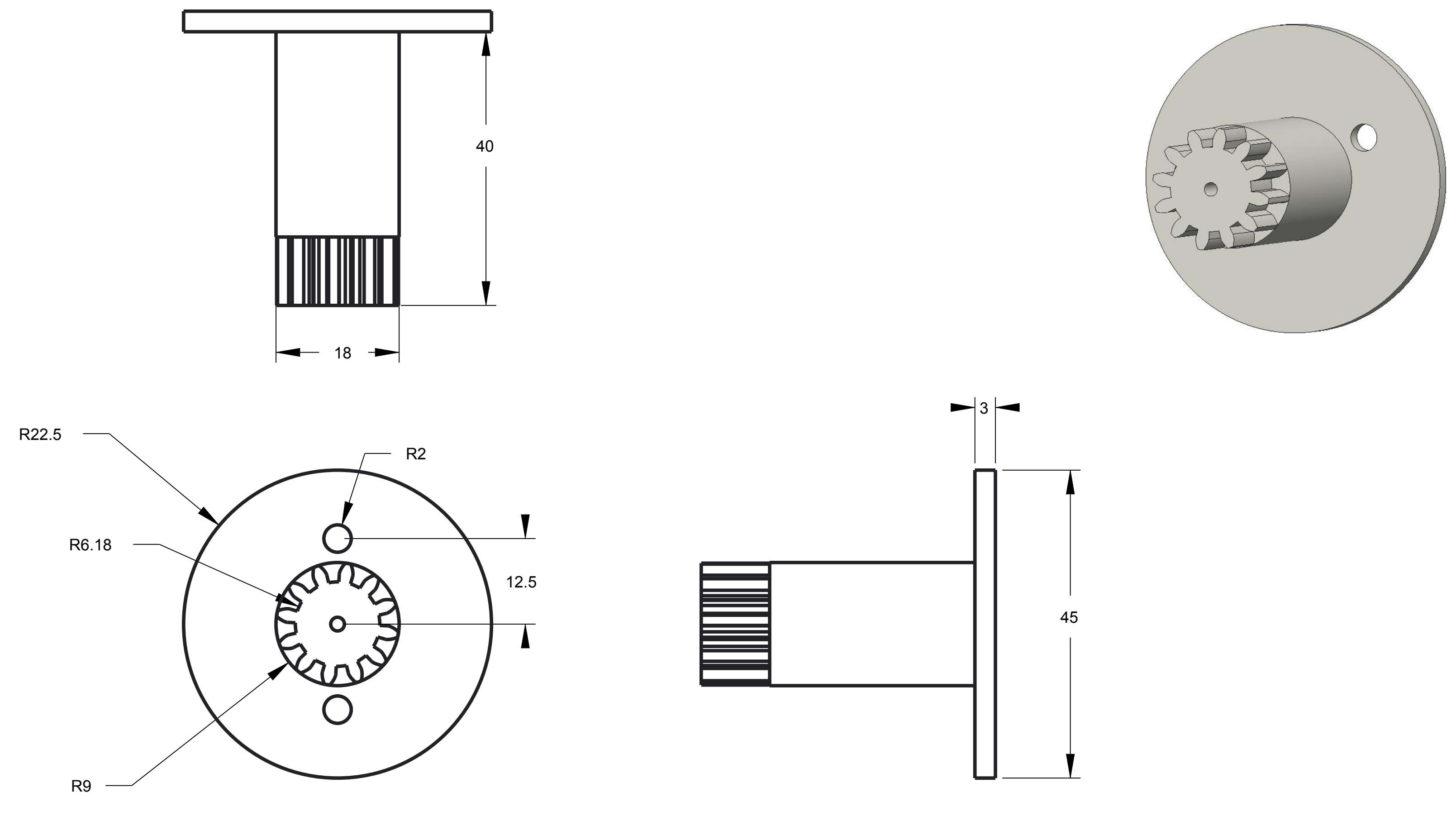
MATERIAL

Qty. 1

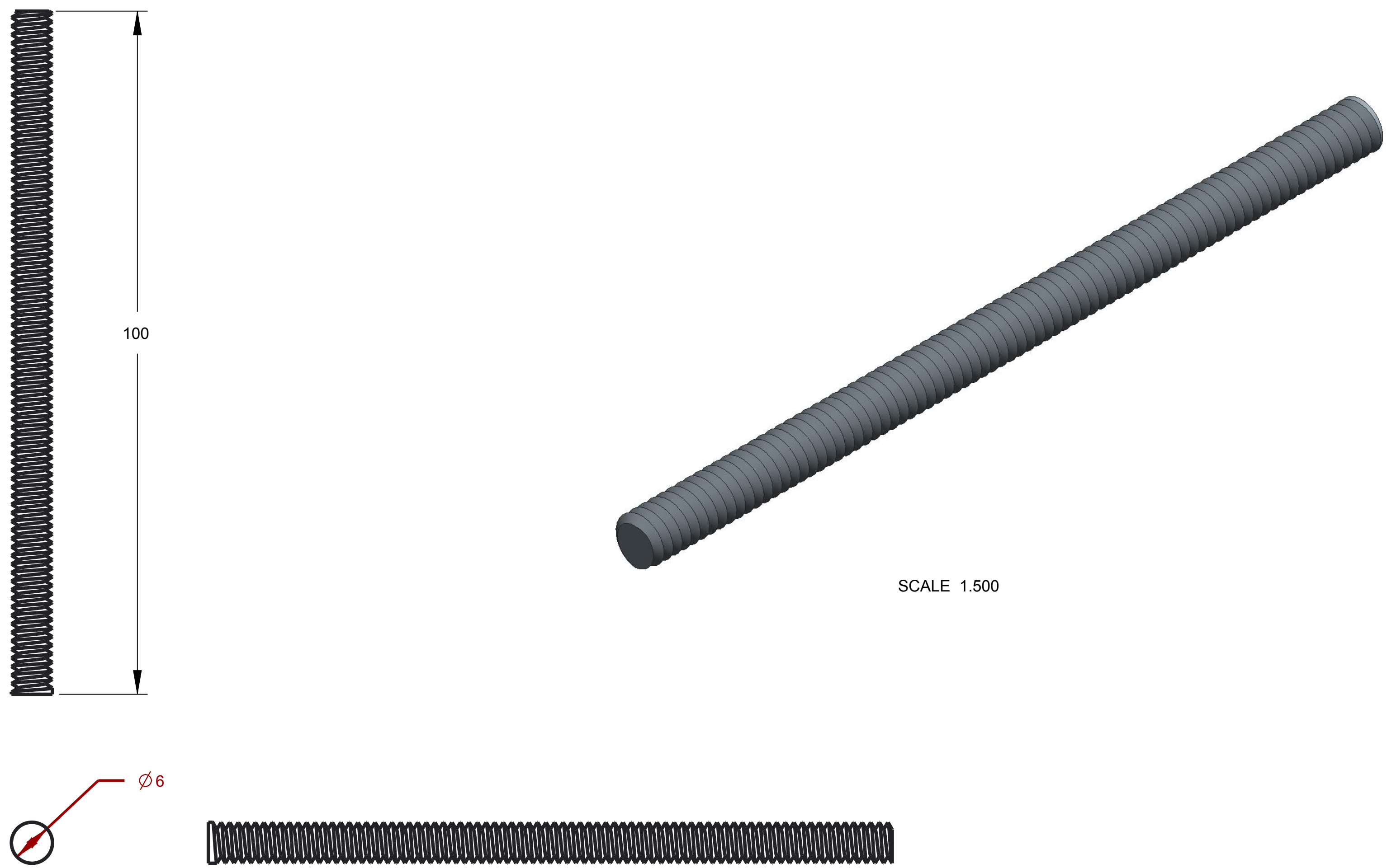
SCALE 1 : 1

SHEET 1 of 1

A4



					DRAWN BY **Manmeet Singh & Nitish Lobo**	TITLE Pinion	
					TUTOR	DEPARTMENT Mechanical Engineering	
					GROUP No.		
Change No.	Name of Item	Changes Made	OK	Date	FILENAME	FILE LOCATION	
ALL TOLERANCES ARE ±0.1mm UNLESS OTHERWISE SPECIFIED		ALL DIMENSIONS IN MILLIMETRES			DATE	MATERIAL	Qty. 1 | SCALE 1 : 1 | SHEET 1 of 1 | A4



Change No.	Name of Item	Changes Made	OK	Date

THE UNIVERSITY OF AUCKLAND
NEW ZEALAND

DRAWN BY: **Manmeet Singh & Nitish Lobo**

TUTOR

GROUP No.

FILENAME

DATE

TITLE: Threaded 6mm Shaft

DEPARTMENT: Mechanical Engineering

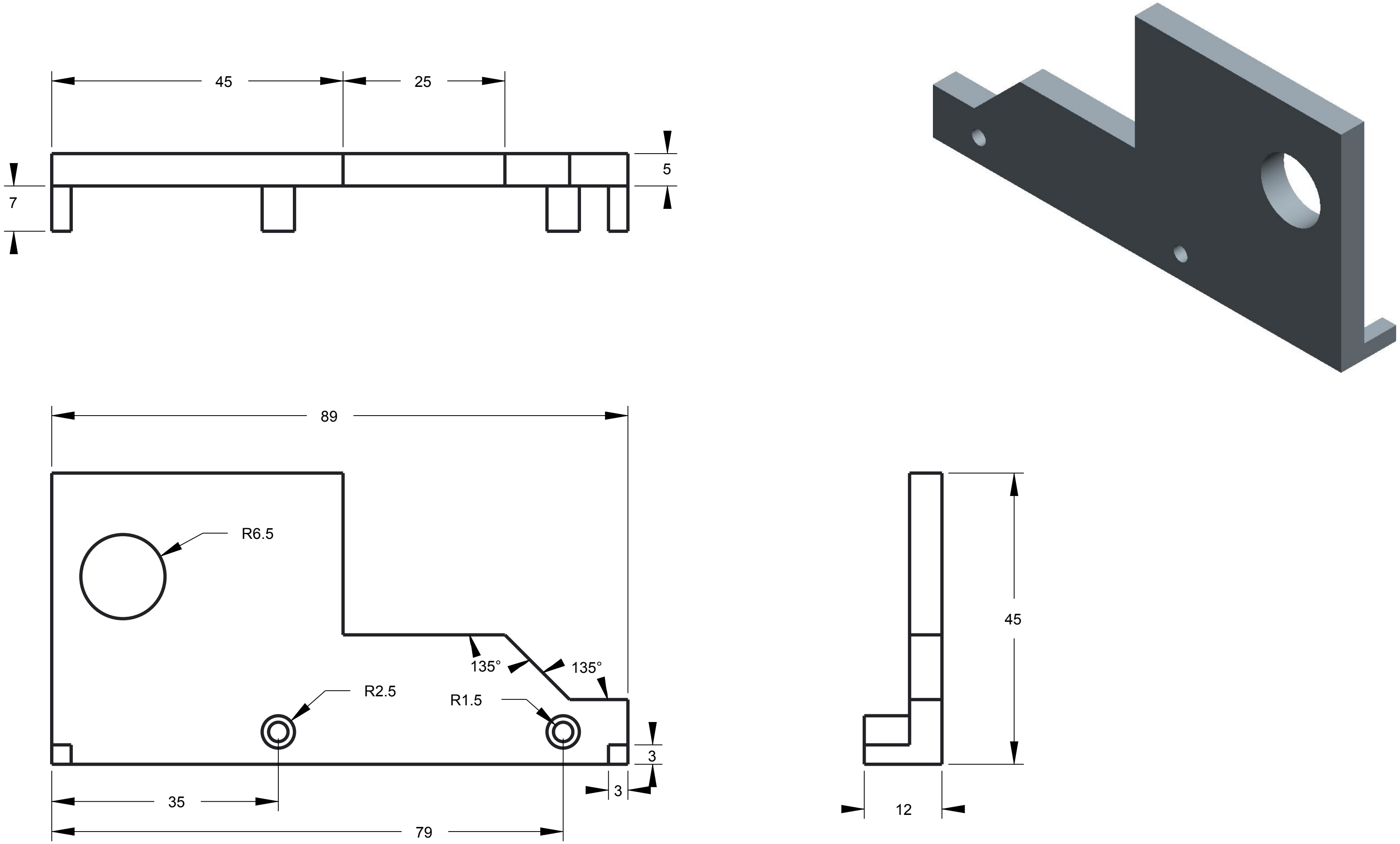
FILE LOCATION

MATERIAL

Qty. 1 | SCALE 1 : 1 | SHEET 1 of 1 | A4

ALL TOLERANCES ARE ±0.1mm UNLESS OTHERWISE SPECIFIED

ALL DIMENSIONS IN MILLIMETRES



					DRAWN BY	TITLE
					Manmeet Singh & Nitish Lobo	Back Plate
					TUTOR	DEPARTMENT Mechanical Engineering
					GROUP No.	
Change No.	Name of Item	Changes Made	OK	Date	FILENAME	FILE LOCATION

THE UNIVERSITY OF AUCKLAND
NEW ZEALAND

ALL TOLERANCES ARE ±0.1mm UNLESS OTHERWISE SPECIFIED	ALL DIMENSIONS IN MILLIMETRES	DATE	MATERIAL	Qty. 1	SCALE 1 : 1	SHEET 1 of 1	A4