Design Optimization of Power Manipulator Gripper for Maximum Grip Force

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***Abstract*— Master Slave manipulators need a gripper with at least 2 Degree of Freedom (DOF). Gripper is used as end effector to carry out complex task in the constrained work spaces. The power manipulator (PM) is one such master slave which reduces the operator load and stress with a power multiplication of 2 to 4 times. The present PM under consideration has a payload capacity of 25 kgf. The grippers used are subjected to higher grip forces than the payloads as they have to use the friction forces to hold. The grippers are designed to have links translating the forces from the motors present above the wrist. If the links are not properly connected and positioned, the performance of the gripper will be affected very badly reflecting a very low payload capacity.**

This paper deals with the modeling of the gripper for the static force analysis in all possible configurations and also the velocity profile, acceleration profile and force analysis of the links in the gripper jaw. The movement of gripper jaws is actuated by screw driven AC servo motor. Gripper force needs to be found to lift a weight up to 25kg-f payload. The optimization of the gripper can be obtained for various parametric values, aiming for all the positions of gripper jaw; the grip force remains same.

***Keywords*— *Power Manipulator, Gripper force, in-cell manipulator*.**

I. INTRODUCTION

Robot grippers are meant to replace human hands because they are very good for repetitive cycles, handling heavy loads, and operate under extreme temperatures and environments where human hands cannot operate. Robot grippers are usually custom designed for particular applications. This paper will discuss in detail about the design optimization of power manipulator gripper for maximum grip force. When motor force is applied upward, the gripper jaws move towards each other. As the gripper jaws grasps objects of various lengths, the grip force applied remains almost the same.

This paper deals with the modeling of the gripper for the static force analysis in all possible configurations and force analysis is done for the links in the gripper jaw (Fig.1). The movement of gripper jaws is actuated by screw driven servo motor. Gripper force is found for lifting weights up to 25 kg-f payload. The optimization of the gripper is obtained for various parametric values aiming for all the positions of gripper jaw.

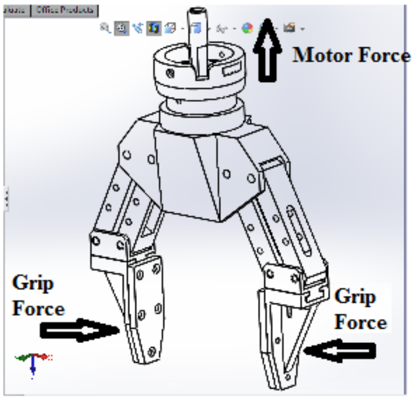
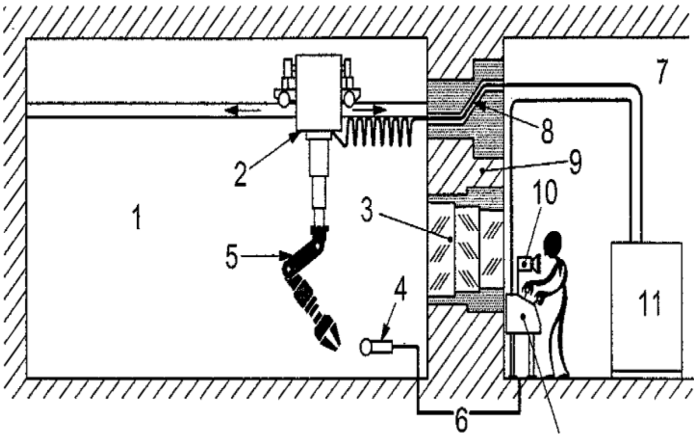


Fig.1 – Force Diagram for Gripper

II. POWER MANIPULATOR

A power manipulator is a mechanical arm combined with a transporter. The manipulator is driven by electric motors and operated by switches or potentiometers and speed control



KEY: 1. Remote in-cell 2. Transporter 3.Shielding window
4. Microphone 5. Mechanical Arm 6. Sound Signal Transmission cable 7. Operating room 8. Transmission cable
9. Sheilding wall 10. Loudspeaker 11. Control cabinet 12. Operating console

Fig.2 — Power Manipulator in remote in-cell

device. The operating console and the control cabinet are located in an operating room (Fig.2). A transmission cable passing through the shielding wall connects the power manipulator in the remote in-cell to the control console.

The mechanical arm, including the transporter, typically has seven to ten motions for designs appropriate to remote in-cells (see Fig.3).

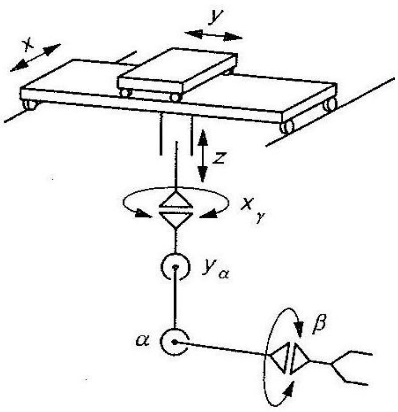


Fig.3 — Power Manipulator (Kinematic diagram)

Description of Power Manipulator

Power manipulator is used for handling heavy loads and performing tasks which do not require force feedback. It is mounted on the crab of the special in-cell crane with common long travel to access full volume of the containment box.

The Power Manipulator (PM) is of modular type for ease of assembly and maintenance inside a high leak-tight containment box with high purity argon atmosphere. The PM has three stages: telescopic Z- axis, azimuth (rotation about vertical axis), shoulder elevation, elbow elevation, wrist elevation and wrist rotation with gripper. The PM is mounted on the gantry bridge with long travel (LT) and cross travel (CT). The PM has six degrees of freedom (6 DOF) in addition to gripper. The PM has a 25 kg-f pay load capacity to handle the various components inside the containment box.

Since the PM has to serve in the containment box, the remote operation and maintenance will be the prime consideration. The PM has a provision to operate by using pendant of push button type with sufficient cable length to facilitate the operations at desired location in the entire length of the containment box.

Description of sub assembly of PM

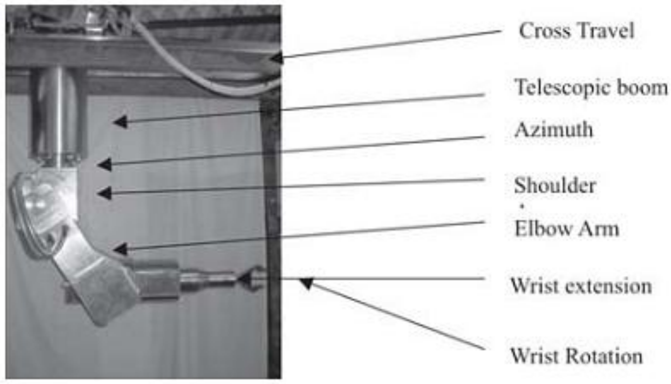


Fig.4— Power Manipulator

A. Bridge Gantry

The bridge gantry is the base for mounting the PM. It has two travels viz. long travel (LT) and cross travel (CT) to cover the entire containment box. The LT (X-motion) and CT (Y-Transverse motion) of PM will be used to track the PM to the required position. The bridge is required to have suitable guide pins for mounting the PM remotely and necessary provisions for cables and connectors. The PM and the bridge crane can be assembled and dismantled through containment top opening. The crab is required to be designed with modularity as prime design criteria for easy remote disassembly of the PM in case of any failure, through the opening above the containment box. The opening will be 3500 mm x 1500 mm.

B. Long Travel

A long Travel (LT) has 16500 mm travel with CT for PM. The LT is wire rope driven. The drive motor and gearbox are mounted inside the containment box. LT run is on square section bar. Wire ropes are provided which will run over the guiding pulleys for LT drives. Manual drive is also to be provided for positioning the lifting hoist in case of failures. A pre-tensioning system is provided for taking up slackness of wire rope.

C. Cross Travel

A Cross Travel (CT) has 4000 mm travel with PM. CT drive motors are mounted on the crab. Double girder design is adopted. The wheel base is designed to accommodate the double girder of the PM.

D. Telescopic Motion

A three stage telescopic motion has a collapsed height (including shoulder and elbow at folded condition) of approximately 2300 mm. Extension of telescopic is 1950 mm Z-motion travel. The telescopic tube is guided precisely with corrosion resistant guide rods or linear slides (Fig.4).

E. Azimuth Rotation

An azimuth rotation about the vertical axis is provided. The rotating mechanism is housed at the top of the fixed telescopic tube. The rotational range of the azimuth is ± 175 degrees about the vertical axis. Motor is compact AC brushless motor.

F. Shoulder Elevation

Shoulder elevation is coupled to the bottom end of telescopic tube. The approximate length of the arm is 600 mm. It has a rotation of ± 100 degrees about the vertical axis. A compact AC brushless inbuilt brake motor is provided inside the shoulder. The motor is controlled through Control panel kept outside the cell. Torque limiting sensor is provided for safety of arm, case of collision.

G. Elbow Elevation

A similar arrangement like shoulder elevation is provided to improve the dexterity of the PM. The approximate length of the arm is 550 mm. It has a rotation of ± 100 degrees.

H. Wrist Rotation

A wrist is provided with endless continuous and reversible rotation of gripper. It is fixed to the end of the wrist. A very compact motor is provided inside the wrist to have the endless rotation. The wrist will rotate about the wrist axis. A failsafe mechanism is adopted in the wrist so that in case of power failure, the gripper does not allow the object to fall freely either because of gravity or due to any other external force. Torque limiting sensors for the axis is provided to limit the damages to the PM caused by over loading.

I. Gripper

A two finger parallel jaw gripper is provided at the end of wrist assembly. A suitable arrangement has been provided in the wrist and its interface to accommodate wrist rotation motor as well as gripper motor inside the wrist body itself. The gripper has the maximum opening of 100 mm. Provision has been made to replace the finger remotely. The arrangement is made to provide necessary gripping force for handling 25 kgf payloads. A force sensor has been provided to control the gripping force. Users can able set the gripping force from the selector depending upon the requirement. Users can set the gripping force in the control panel depending upon the nature of the object being handled. Speed of each axis can be varied using the pendant according to the requirement. (Fig.4) shows the photograph of the parallel jaw grippers used in the power manipulator.

III. DIMENSIONAL AND TRAVEL REQUIREMENTS OF PM

	Specification	Speed
Long Travel (L.T)	16000mm	0-75 mm/s
Cross Travel (C.T)	3000	0-75
Overall length of PM when fully	4780 mm	
Overall length of PM when fully	2300 mm	
Length of shoulder (approx)	550 mm	
Length of Elbow (approx)	450 mm	
Vertical motion of telescopic tube	1950 mm	0-20 mm/s
No. of stages in vertical motion	3	
Azimuth rotation	± 175	0-15 deg/ s
Shoulder elevation	±	0-15 deg/s
Elbow elevation	± 100	0-15 *deg/*
Wrist rotation	Endless	0-30 deg/s
Gripper opening	0 -100 mm	0-15 mm
Pay load (job weight)	25 kgf	

Table.1 – Overall dimensional and motion requirements

IV. CASE STUDIES

Case Study 1 : Four Bar link Mechanism

A four-bar linkage, also called a four-bar, is the simplest movable closed chain linkage. It consists of four bodies, called bars or links, connected in a loop by four joints. Generally, the joints are configured so the links move in parallel planes, and the assembly is called a *planar four-bar linkage*.

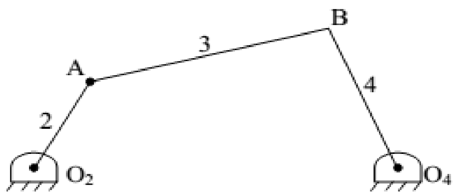


Fig.5 — Line Diagram of Four bar link

Velocity analysis for four bar mechanism is done in manually and graphically. During the analysis, observation was made that the double rocking or crank-rocker motion between the links as in Grashof's criteria. And during crank-rocker motion, there the system loses one degree of freedom as in Gimbal lock.

Velocity (mm/s)	Velocity Diagram (Manual) (mm/s)	Graphical (mm/s)
V_A	18600	18600
V_B	12600	12600
V_{AB}	20100	20100

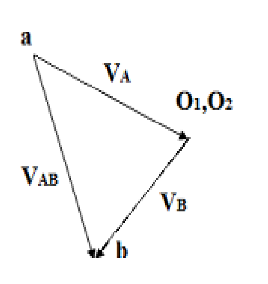


Table 2 — Velocity analysis of four bar mechanism (Crank at 60^0, Angular speed ω = 62.8 rpm/s, N=600rpm)

Grashof's criteria *(also called Grashof's Law)*

Grashof's criteria is applied to pinned four bar linkages and states; "*The sum of the shortest and longest link of a planar four-bar linkage cannot be greater than the sum of remaining two links if there is to be continuous relative motion between the links."* Below are the possible types of pinned, four-bar linkages(fig.6)

$$s + l < p + q$$

l = length of the longest link
s = length of the shortest link
p, q = length of the two intermediate links

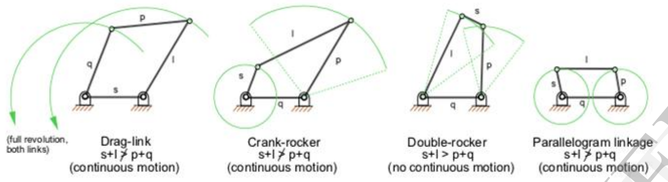


Fig.6— Grashof's criteria

Gimbal lock

Gimbal lock is the loss of one degree of freedom in a three-dimensional, three- gimbal mechanism that occurs when the axes of two of the three gimbals are driven into a parallel configuration, "locking" the system into rotation in a degenerate two-dimensional space.

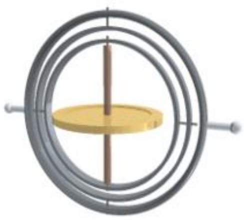


Fig.7— Gimbal with 3 axes of rotation

Gimbal with 3 axes of rotation(Fig.7). A set of three gimbals mounted together to allow three degrees of freedom: roll, pitch and yaw. When two gimbals rotate around the same axis, the system loses one degree of freedom.

Case Study 2: Slider Crank Mechanism

A single slide crank chain is a modification of basic four bar chain. It consists of one sliding pair and three turning pairs. It is usually found in Reciprocating steam engine mechanism. This type of mechanism converts rotary motion into reciprocating motion and vice versa (fig.8).

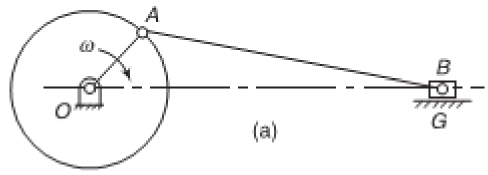


Fig.8 Slider Crank Mechanism

Velocity (mm/s)	Velocity Diagram (Manual) (mm/s)	Graphical (mm/s)
V_A	12600	12600
V_B	11700	11700
V_{AB}	9300	9240

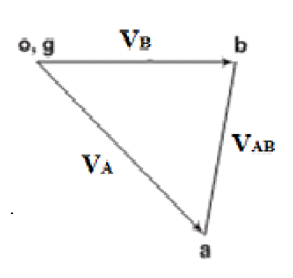


Table 3 — Velocity analysis of slider crank mechanism (crank at 45^0 Angular speed ω= 62.8rpm/s, N=600rpm)

Acceleration (mm/s²)	Acceleration Diagram (Manual) (mm/s²)	Graphical (mm/s²)
A_A	788768	788768
A_B	555000	555000
A_C	570000	570000
$BA\alpha_3$	525000	525000
$CA\alpha_3$	360937.5	360937
$\frac{V^2 CA}{CA}$	120272.7	120272
$\frac{V^2 BA}{BA}$	180187.5	180187.5

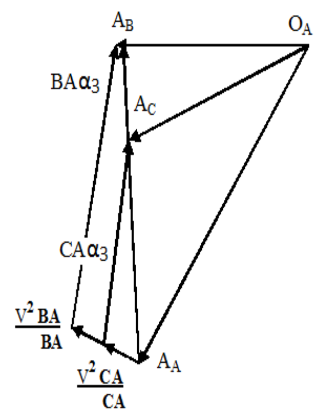


Table 4 — Acceleration analysis of slider crank mechanism (crank at 45^0 Angular speed ω= 62.8rpm/s, N=600rpm)

Table 3 and Table 4 give the details of velocity and acceleration analysis of slider crank mechanism. The crank of the mechanism is at 45^0, angular speed of crank is ω= 62.8rpm/s, with speed,N=600rpm.

Case Study 3: Quick Return Mechanism/ Shaper Mechanism

The usual kinematics system provided in shaping machine for transmitting power and motion from the motor to the tool and job at desired speeds and feeds is schematically shown in Fig.9.

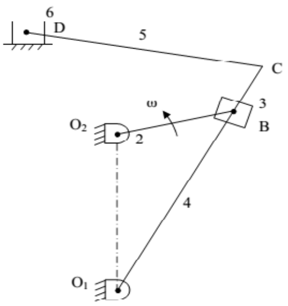


Fig.9—Configuration diagram of Quick return mechanism

In this inversion of the slider-crank the slider guide link is made to rotate. This is called a quick-return mechanism. This linkage also converts rotary motion of the crank into oscillatory angular motion of the slider guide link. In a crank and slotted lever mechanism, crank O2 A rotates at ω rad/sec in counter clock wise direction as in fig.9. The same has been modeled in modeling software and kinematic analysis software. The displacement of the slider with respect to rotation angle of crank is shown in fig.10.

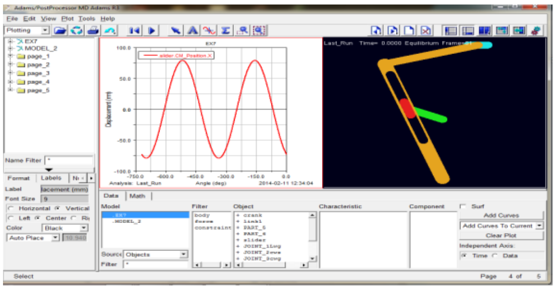


Fig.10 - Quick Return Mechanism in Modelling and Kinematic analysis software, graph depicting about displacement of slider with respect to rotation angle of crank

Table 5 give the details of velocity analysis of Quick return mechanism/ shaper mechanism. The crank of the mechanism is at 45^0, angular speed of crank is ω= 62.8rpm/s, with speed,N=600rpm.

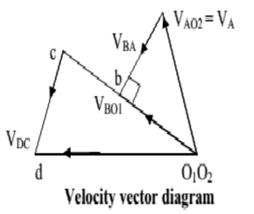
Velocity	Manual (mm/s) $x10^4$	Graphical (mm/s) $x10^4$	
V_A	1.88	1.90	
V_{BO}	1.40	1.50	
V_{DC}	1.20	1.20	
V_{BA}	1.35	1.34	

Table 5 — Velocity analysis of Quick return mechanism

V. CALCULATIONS

A. Manual Calculations

The calculation is done for various gripper opening from 20mm to 90mm. The line diagram of one side of the gripper is shown in fig.11.

For SS304 material of gripper pad and specimen object of various lengths, the coefficient of friction, μ = 0.4. The formulae used are

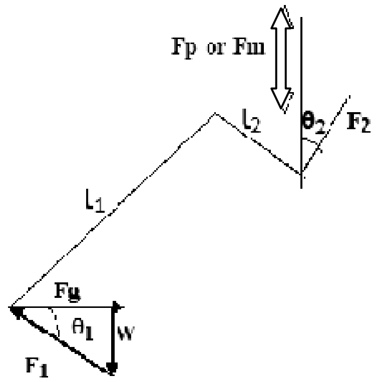


Fig.11- Line diagram of gripper

Resultant force of weight is W and gripping force Fg is F_1.

$$Fg = \frac{W}{\mu} \quad \text{and} \quad F_1 = \frac{Fg}{\cos\theta_1} \quad , \quad F_2 = \frac{F_1 . L_1}{L_2}$$

As motor force, Fm or Fp is applied in vertical line

$$F_P \text{ or } F_m = \frac{F_2}{\cos\theta_2}$$

For W = 10.05 kg and μ = 0.4,

$$Fg = \frac{W}{\mu}$$

Fg = 10.05 / 0.4 = 25.125 kg

For gripper opening length = 90 mm,

$L_1 = 52$ mm, $L_2 = 40.23$ mm, $\theta_1 = 29.9^o$, $\theta_2 = 19^o$

$$F_1 = \frac{Fg}{\cos\theta 1}$$

$F_1 = 25.125 / \cos 29.9^o = 28.98$ kg

& $L_1 = 52$ mm, $L_2 = 40.23$ mm then

$$F_2 = \frac{F_1 . L_1}{L_2} = 28.98 \times 52 / 40.23 = 37.46 \text{ kg}$$

$$F_P \text{ or } F_m = \frac{F_2}{\cos\theta_2}$$

Fm = 37.46 / Cos 19 ^{o} = 39.62 kg-f

Similarly, calculations for lengths 20mm to 80mm are done and tabulated in Table.6. It can be seen that the motor force increases with increase in length of gripper opening.

B. Experimental Calculations

Experiment was conducted on power manipulator gripper for various gripper openings, Fig.12 shows the weight 10.05 kg, specimen lengths from 20 to 90mm and PM tong in opening position. PM tong was actuated by pendant push button station which provides selection of all axes with varying speed control in small increments.

Fig.12 – PM gripper, weight 10.05kg and specimen in various lengths

Fig.12 shows the experimental setup in which robot arm, wrist/ gripper, weights and specimen lengths can be seen. All the experimental values including motor force were obtained from the display board. Fig.14 shows the graphical representation of motor force versus gripper opening for various lengths. The grip force is plotted against motor force in Fig.13. We can observe that there is a linear relation between motor force and grip force.

Gripper opening (length of the object) mm	Motor force in kg Experimental value for 10.05kg	Motor force Calculated Value in kg	Grip force in kgf
20	35.76	34.53	26.02
30	31.5	34.64	22.85
40	34.14	34.52	24.85
50	35.58	35.01	25.53
60	32.46	35.73	22.83
70	34.68	36.52	23.86
80	37.74	37.86	25.05
90	27.78	39.62	17.62

Table 6 – Motor Force comparison between experimental and manual calculations

The graph (Fig.14) gives details of calculated values for various positions of gripper opening. From the graph, it can be seen that motor force increases linearly as the gripper opens. For calculations 10.05kg weight is considered. The same weight is considered for experiment and the experiment is done for various opening of gripper starting from 20mm to 90mm in steps of 10mm. There is a difference between experimental and calculated values of motor force which is due to sliding joints, revolute joints, links and their position in between the application of motor force to point of grip force. These links and joints increase or decrease the motor force according to the position and friction between them.

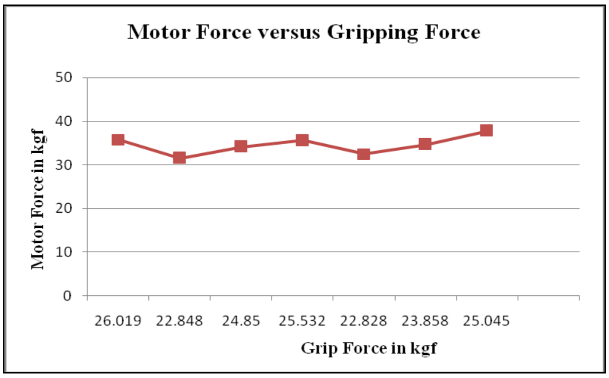


Fig.13 – Graphical representation of motor force versus grip force

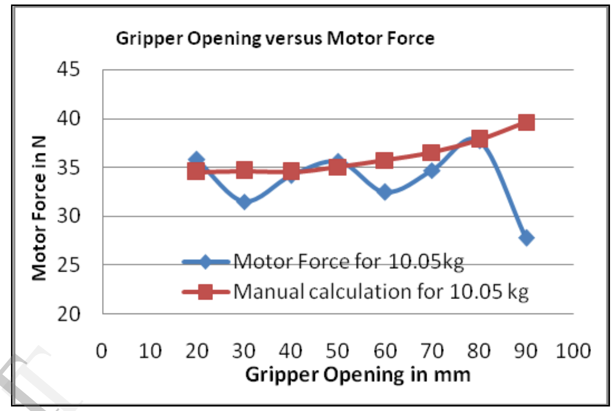


Fig.14 - Motor Force graphical comparison for various lengths

CONCLUSION

- The difference between experimental and calculated value of motor force is due to various links, joints between the links and their positions.
- Grip force for various grip openings for targeted load is obtained. The targeted load is kept constant at 10.05kg and various grip force is obtained for different openings.
- Higher the fineness of the serration on pads, higher is force required to grip the object and higher is the tendency of the object to slip from the gripper jaws.
- For lifting loads, grip force is required to be applied on the gripper pads at the centre of gravity of the object.
- Use of power manipulator enables the operator to handle objects much heavier than his capacity, without any stress.
- By using modeling software, gripper is modeled and analyzed for various positions of gripper opening.
- Grip force applied is limited to the weight required to handle the object, to avoid any damage to the object.

- The grippers used are subjected to higher grip forces than the payloads as they have to use the friction forces to hold.
- Co-efficient of friction varies inversely to variation in size of serration on the pads. As coefficient of friction decreases, grip force increase. Conversely as coefficient of friction increases, grip force decreases.

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