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TWO-FINGERED SERVO GRIPPER WITH FOUR-BAR MECHANISM AND ROLLING AS AN INTEGRATED FEATURE

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Abstract

Two-fingered parallel grippers often use Four-Bar mechanism with gears to operate both the fingers. This paper describes the development of the similar type of gripper (modeled on CREO and 3-D printed working model with ABS material) with two DC servo motors for the respective fingers instead of gears, because these motors have standard sizes and are easily available in the market. As an integrated feature, the rolling of complete gripper assembly is provided about the shaft of another servo motor attached to the gripper body. Also, an additional embracement plate allows the Four-Bar mechanism to move in a plane making the fingers stable and firm while loading and unloading the external object of varying size from 15mm to 80mm. The configuration diagrams and the force vector diagrams are drawn on AutoCad 2016 for every 5° motion of crank, and thus, the gripper force is calculated. The developed model was used in articulated robot for simple pick and place operations.

Keywords:
parallel gripper;
two fingers;
high gripper ratio;
4-bar mechanism;
servo motor;
pick and place;
gripper design.

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1. Introduction

Robots are now a commonplace in the large industries that involve repetitive tasks or require humans to carry out hazardous operations. A typical industrial robot can be divided into three parts namely a wrist, an arm, and the base or body, with the help of which it can perform a range of actions upon the workpiece: picking, manipulating, transferring, placing and releasing the workpiece in a discrete position, depending on what the industrial requirements. To perform these operations, different kinds of mechanisms can be employed using bars and gears which are studied by Petrescu *et al.* [9].

However, when the operation involves pick and place of the workpiece, specifically, gripping mechanism is used in the design of industrial robots which is discussed by El-Kalay *et al.* [8]. This pick and place operation is implemented using a jaw type end-effector, known as gripper, which is attached to the wrist. Thus, the gripper acts as an interface between the robot and its working environment.

Liao and Liao *et al.* [1], [4] has explored these possibilities for the jaw of the end-effector based on a modified Scott Russell straight-line mechanism for its motion while transferring workpieces in and out of a machine or assembly. They analysed the clamping force and stress of the end-effector and determined the accuracy of the trajectory. Similarly, Bejczy *et al.* [2] discuss the end effectors as an integral part of telerobot systems which are employed in the space and significantly impacts on the tele manipulation performance.

Mravlje *et al.* [5] provided the basic guidelines to design the grippers which use vacuum cups to grab the workpiece. Costo *et al*. [3] also made use of the same gripping technology. They discussed a re-configurable, three-fingered gripper, based on three vacuum cups to pick up and handle the limp sheets of leather and attempted the automation of leather manufacturing industries that eventually speed up the production of shoes.

Hassan and Abomoharam [6] discussed a gripper which is a single DOF system with four fingers that can be used for pick and place different type of objects or in other automation processes. The four fingers are operated using 4-bar mechanism. An electric motor is used to drive one finger and this motion is passed to the other fingers by a slider-crank mechanism, for which they developed a prototype, tested it and performed the study of geometric and kinetic models of the gripper. Roy *et al.* [7] had also discussed the design and analysis of the 4-bar mechanism in their papers.

In this paper, we have developed a gripper that has two-fingers in place of vacuum cups, as shown in [3] and [5], to grab the object. The gripper uses two standard micro servo motors as a replacement of gears [9] to run the crank of 4-bar mechanism. Moreover, unlike [6] that use one electric motor and slider-crank mechanism, we have designed a two-fingered gripper that use two servo motors, one for each finger, which is operated through Arduino. Also, moving links of the 4-bar mechanism is made to lie in a single plane during the pick and place operation with the help of aluminium embracement plate attached to the front of the gripper body.

Another novel idea has been attempted in this paper which is related to the wrist of the arm, where the gripper can be attached. The wrist in a robotic arm requires three movements which are yaw, pitch and roll. The idea is to roll the complete assembly of gripper about the shaft of the third servo motor which forms a part of the gripper body itself. This assembly arrangement had successfully provided the roll movement of wrist to the gripper itself, thereby making the whole system of wrist and gripper compact.

For every 5° motion of the crank, which is driven by motor, configuration diagrams are drawn and the measurement of the angle turned by the coupler (finger) and the rocker are recorded. Also, the gripping force of fingers is obtained from the vector diagrams for every 5° motion of crank, both of which are drawn on AutoCad 2016.

The following sections discuss the assembly of the designed end-effector, use of Four-Bar mechanism, kinematic and kinetostatic synthesis of the end-effector. The tables and graphs were plotted to enhance the understanding of the results obtained by the analysis.

2. Assembly of End-Effector

The gripper consists of sub-assembly parts including three servo motors, two fingers with four bar mechanism, front and rear embracement plate, spherical ball support cage and aluminium bracket to connect gripper with the pitching motor of wrist in the robotic arm. Figure 2.1 shows the entire assembly of the end-effector.

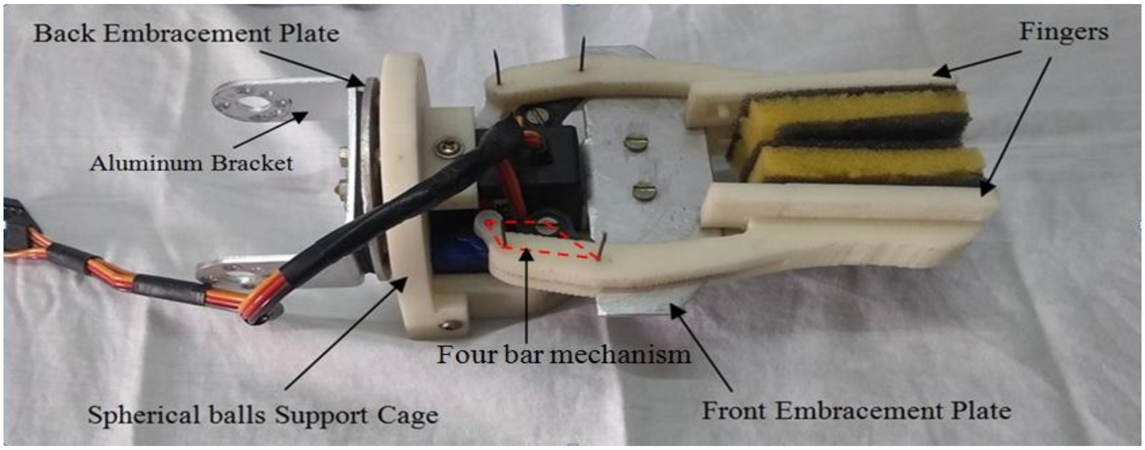

Figure 2.1 *Complete Assembly of Gripper*

All parts of the end effector that is developed in this paper are modelled on CREO and are 3-D printed using ABS (Acrylonitrile Butadiene Styrene) material, which is light in weight and can bear safe stress up to 30 Mega Pascal. The two aluminum embracement plates are used to make the complete assembly rigid and bear more loads.

2.1 Gripper Body

The gripper body or casing, as shown in the Figure 2.1.1, is the main part of gripper which is featured with all the geometrical requirements so that it can accommodate the sub-assembly parts. Total allowance of 200 microns was provided for the ease of assembly and to compensate shrinkage which takes place during the cooling of 3-D printed object. The shrinkage observed was nearly 50 microns in a 50 mm size of object which was manufactured on machine **Accucraft i250+** from **Divide By Zero**.

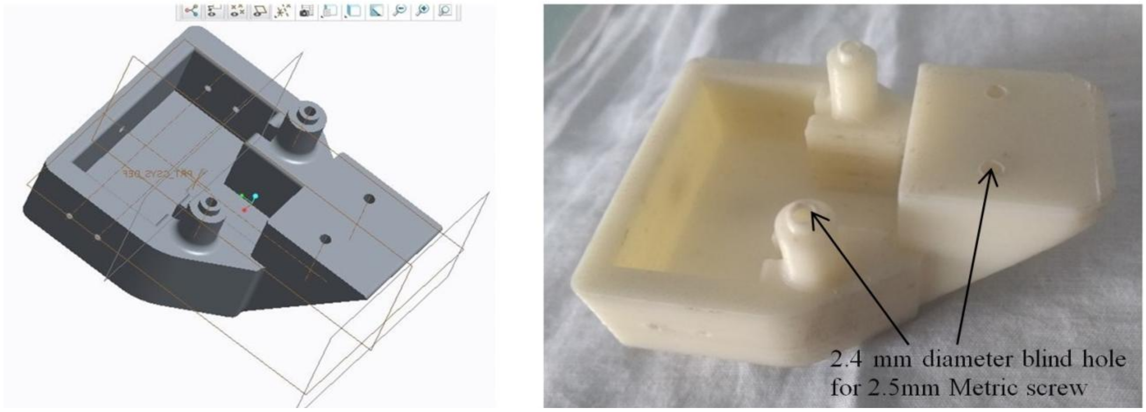

Figure 2.1.1 *CREO model and 3-D printed gripper body*

2.1.1 Evolution of Gripper Body

Before the design (as shown in the Figure 2.1.1) was finalised, many other designs were modelled and checked for their functionality. A thorough comparison was made between them and the best design as per the geometrical requirements was selected as the gripper body of the end-effector. Figure 2.1.1.1 shows the evolution in the designs of the gripper body.

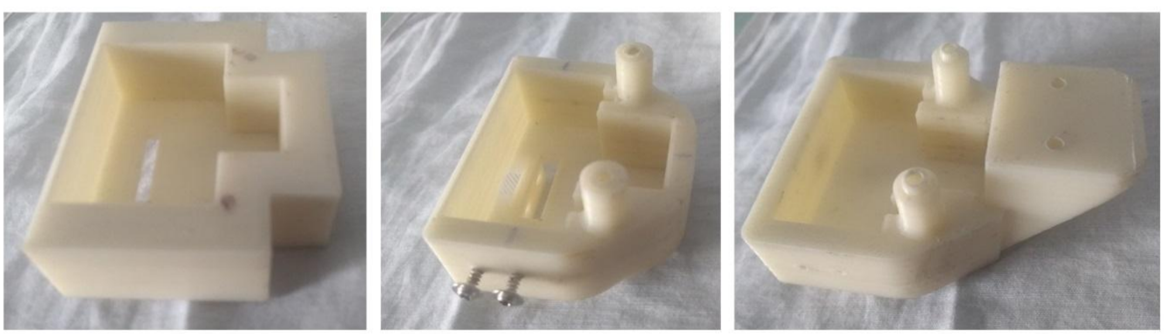

Figure 2.1.1.1 *Evolution of the gripper body (from left to right)*

2.2 Actuator

In this gripper, we have used three DC servo motors as actuators, which get press fit in the gripper body. These motors, which have standard sizes, were specifically chosen because of their easy availability in the market.

Two Micro Servo SG-90 motors are used for energising each of the crank-rocker mechanism where the coupler acts as a finger. Another servo motor, RKI 1206, is used as the central motor that provides rolling to the complete gripper assembly about its own shaft. The assembly of motors is shown by the Figure 2.2.1.

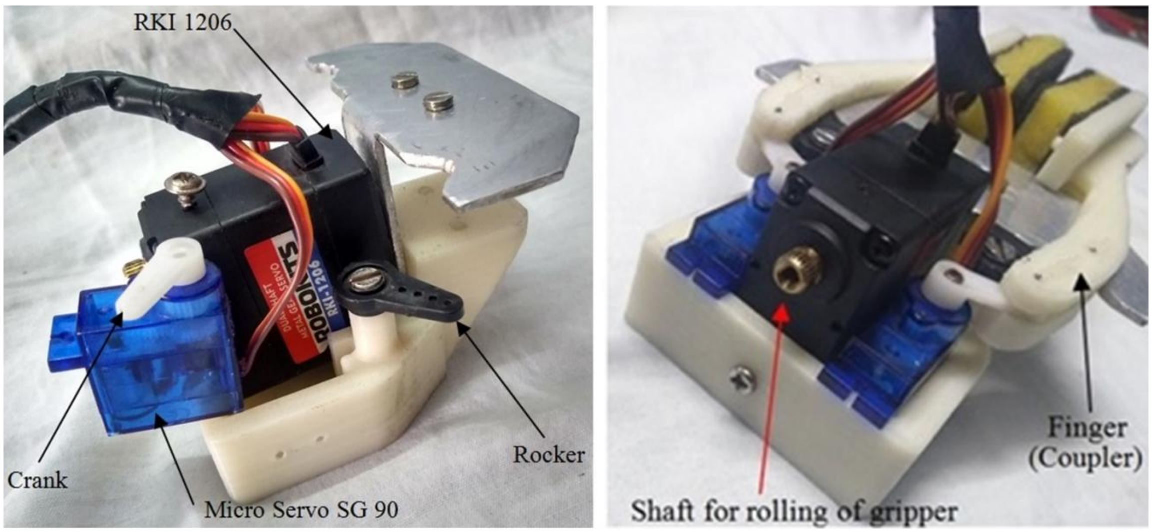

Figure 2.2.1 *Arrangement of Motors in the Gripper Assembly*

2.3 Fingers with the Four-Bar mechanism

To design the fingers, many geometrical models were keenly observed and trials were made with small variations in the link length of Four bar mechanism and the most suitable geometry was selected so as to comply with the crank and rocker mechanism and the same profile was extruded to get the final shape of the gripper finger with little modifications as per the requirements. Figure 2.3.1 shows the trials to select the profile of the fingers.

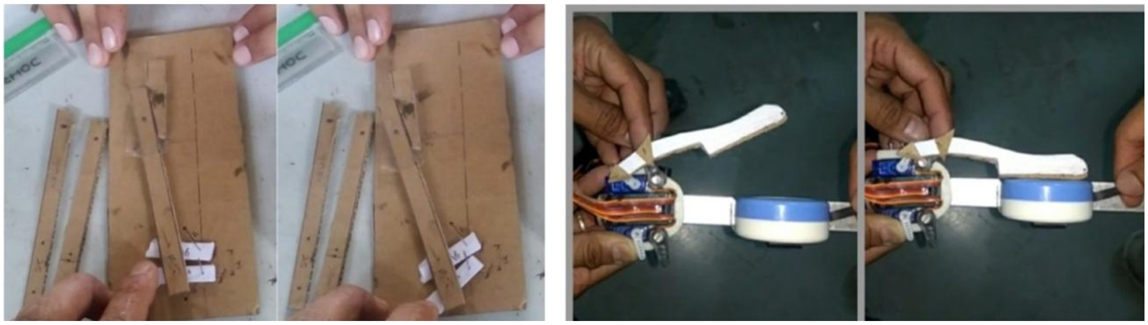

Figure 2.3.1*Trials to determine the finger profile*

A slit of 2.4 mm was cut through the fingers so that it can align with the front embracement plate. A cushion was also attached to the gripper for smooth handling of the objects. It was kept soft enough to deform about 3 mm at a load of 450 grams-force which was selected to comply with the actuator force. These fingers can grab an object of size ranging from 15mm to 80mm. The model so obtained was 3-D printed and finally, was ready to be assembled to the gripper, as shown by the Figure 2.3.2.

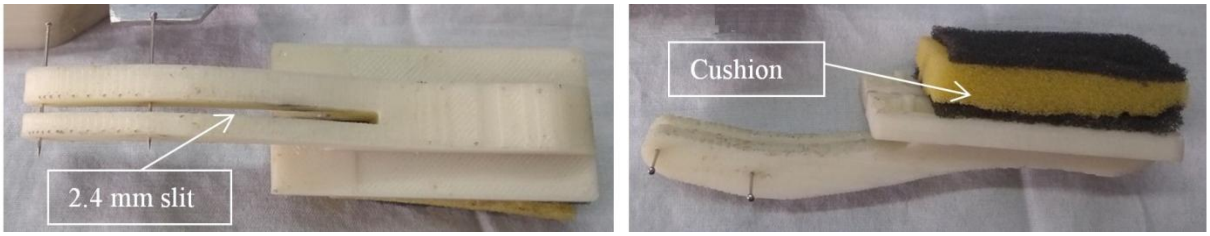

Figure 2.3.2 *Finger after 3-D Printing*

2.4 Front Embracement Plate

The front aluminium embracement plate (as shown in Figure 2.1) is fastened to the body by two top screws and a locking screw. The plate serves as a guide to move crank, rocker and the finger (coupler) in a single plane and provide distributed support to the finger so as to avoid concentrated stress at any section on it.

2.5 Rear Embracement Plate and Spherical Ball Support Cage (Provision for Rolling of Gripper)

Pitching, yawing and rolling are the functional parts of wrist for a robotic arm to which the gripper is attached. Here, as an additional feature, we have integrated rolling in the gripper body itself. This reduces the complexity of the wrist with no significant increment in the weight of the wrist or the gripper. Thus, a robust design of gripper is obtained.

To reduce the bending stress of shaft about which the gripper rolls, a circular, aluminium plate (for embracement) is provided with six spherical balls in support cage as shown by the Figure 2.5.1. Also, the disassembled sub-assembly is shown by the Figure 2.5.2 for the better understanding of this Part of the gripper assembly.

This arrangement will allow the shaft to have only tensile stress and no bending. Thus, it will increase the load bearing capacity of the shaft, which can further allow it to increase payload.

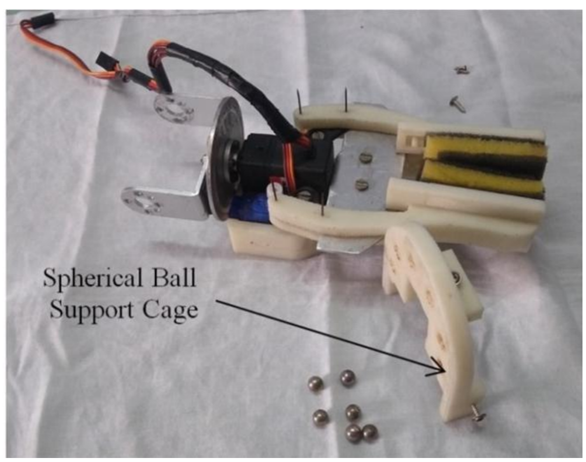

Figure 2.5.1 *Spherical balls support cage (Assembled and Disassembled)*

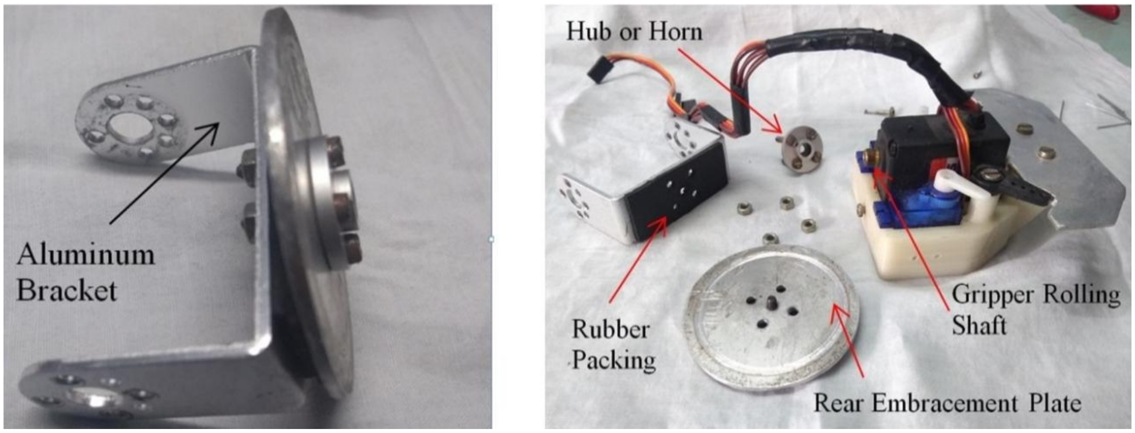

Figure 2.5.2 *Rear Embracement Plate (Assembled and Disassembled)*

To understand the function of rear embracement plate, a comparison between two cases, (a) and (b), is shown by the Figure 2.5.3. In case (b), spherical ball(s) becomes the load carrying component (only compressive force), which will induce tensile stress and completely eliminate the bending stress from the shaft. Hence, the gripper will be able to bear more loads in case (b), as compared to case (a) where no spherical balls are used.

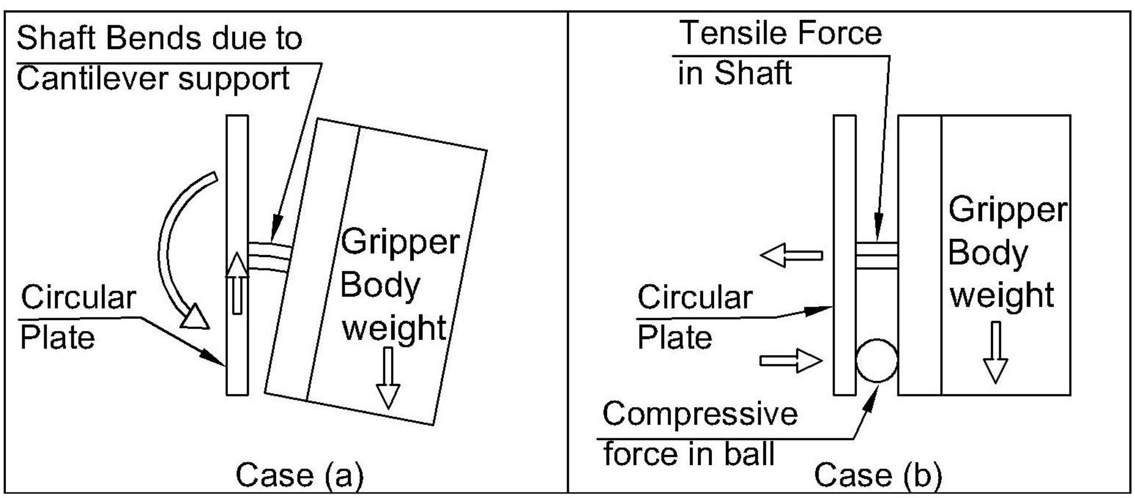

Figure 2.5.3 *Eliminating bending stress from the shaft using a Circular Plate with spherical balls*

3. Kinematic Synthesis and Four-Bar Mechanism

The kinematic synthesis of the gripper includes the method used for the selection of links of four bar mechanism which provides motion to the fingers of the gripper. For the pick and place task, we have worked on the configuration diagrams for every 5° of motion of crank. In the following sections, we have performed the complete geometrical analysis of the robotic finger.

3.1 Selection of Links for Four-Bar Mechanism

In our mechanism, the fixed link is the part of gripper body and the selected motor assembly. The length of this fixed link, as shown in the Figure 3.1.2, came out to be 13.25 mm which was un-modifiable because of the rigid gripper casing. The maximum length of the crank and the rocker was 15mm and 17mm respectively.

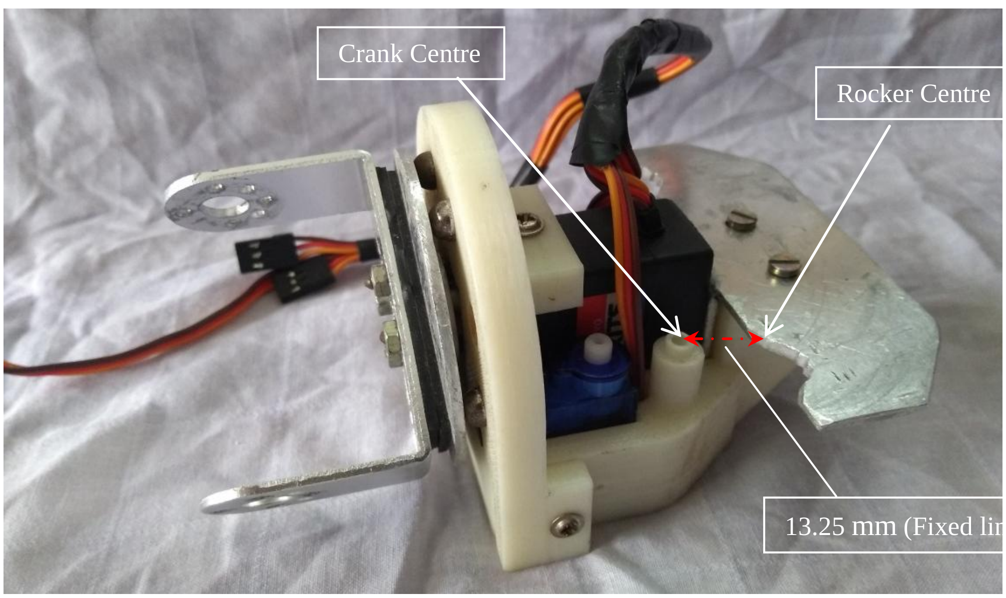

Figure 3.1.2 *Length of the fixed link in the gripper*

In order to select the length for the three links named as crank, coupler and rocker, the following procedure was followed. Initially, these lengths were arbitrarily taken to be 15 mm, 20 mm and 17 mm respectively. These lengths were then varied on Mechanalyser Software using the hit and trial method. For every 1 mm variation, we got the following observations:

- When the crank length was decreased, the crank traversed larger angle for the same angle turned by rocker.
- When the coupler length was decreased, it resulted in large sweeping of the finger and also, opened the gripper wider causing the coupler to traverse a larger angle.
- When the rocker length is increased, it caused less sweeping of finger and permitted almost the parallel jaw movement during opening or closing.

After hit and trial, the suitable lengths of the crank, rocker and coupler were decided as 11 mm, 17 mm and 21 mm respectively, which resulted in a Non-Grasshoff's chain i.e.

$L+s>P+q$,

Where, L=coupler length (longest), s=crank length (shortest), P and q are the lengths of other two links.

3.2 Configuration diagrams for each 5°change of crank angle from its initial position (fully closed)

AutoCad is very useful and time saving software that is best suited for repetitive tasks in 2-D drawing. Using the same software (version 2016), we have drawn the positions of the crank in completely closed and completely open state, which matches the actual dimensions of the developed model (Figure 3.2.1). Following which, configuration diagrams of finger were made for every 5° change of crank angle with respect to its initial position that is when the finger is in closed position.

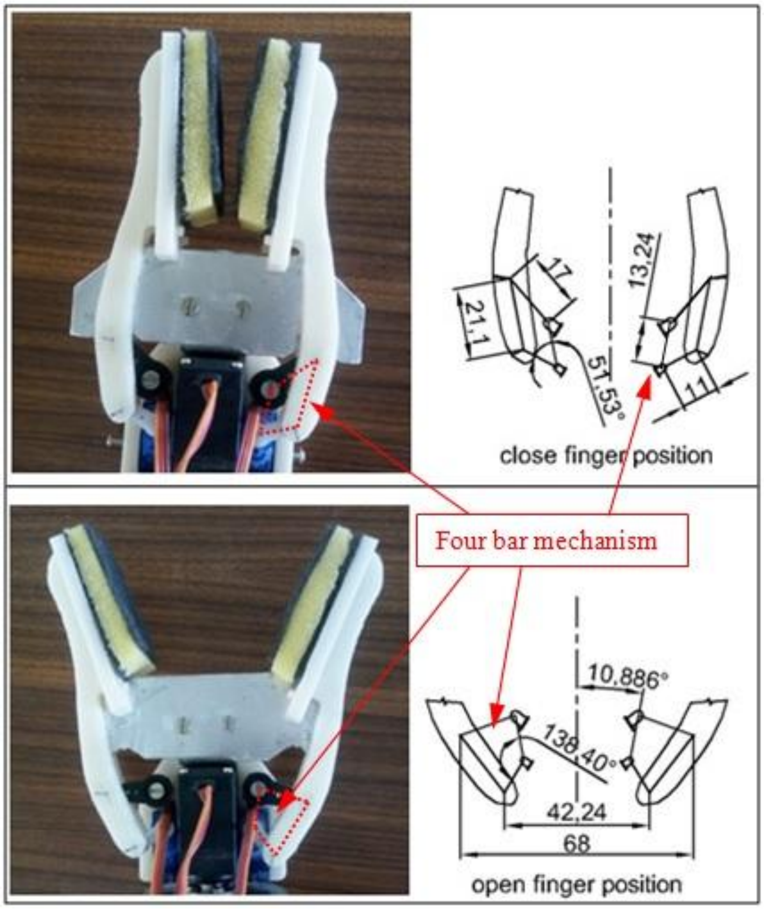

Figure 3.2.1 *End-Effector in the extreme positions*

The configuration diagrams are given below with single point tracing on the finger. To summarize, the diagrams presented in the paper are showing variations for every 15° motion of crank angle. (Figure 3.2.2)

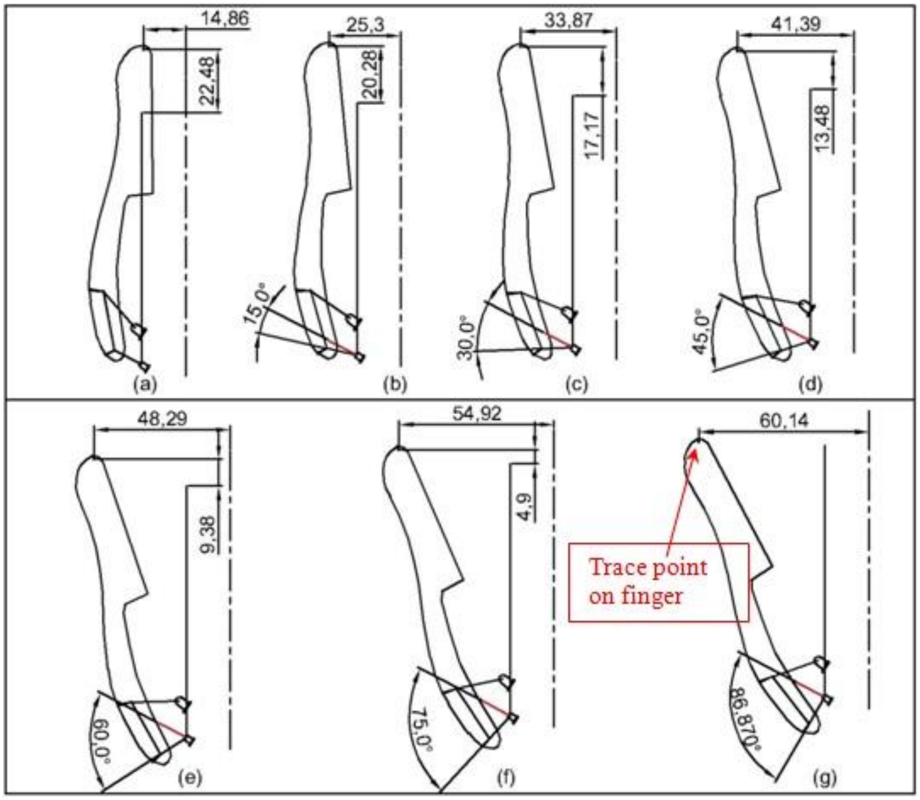

Figure 3.2.2 *Configuration diagrams for every 15° of crank movement from completely closed position*

4. Kinetostatic Analysis of the Gripper

Figure 4.1 shows the free body diagram of coupler (finger of the gripper) when it is fully closed.

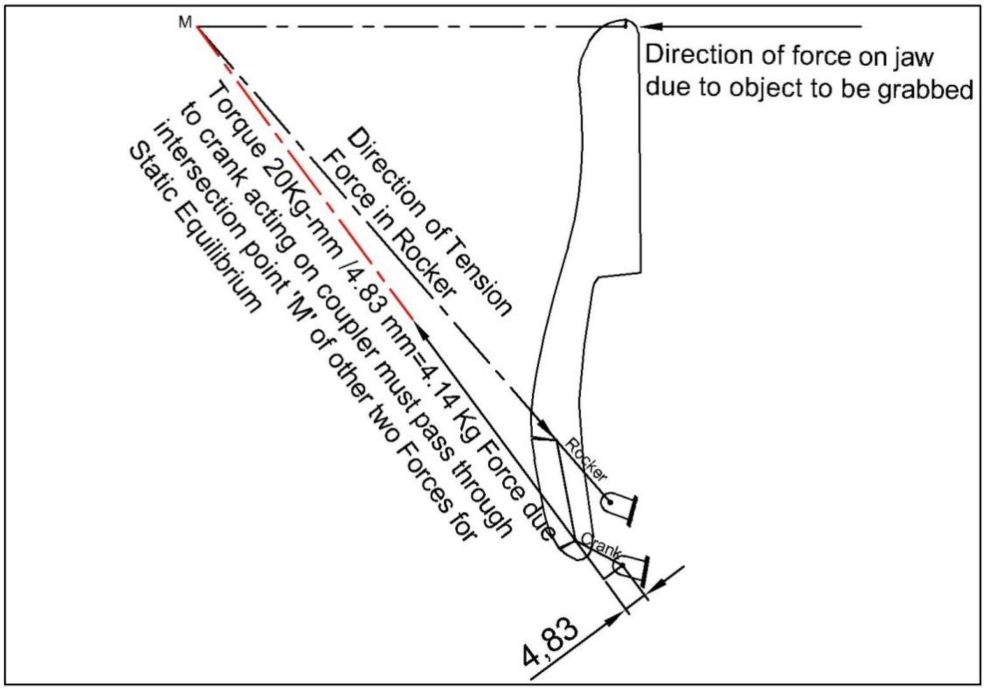

Figure 4.1 *Configuration Diagram when fingers are in fully closed position*

Three forces are acting on the finger which are as follows:

(i) Reaction Force of the grabbed object (Direction is known, which is horizontal)

(ii) Tension in Rocker (Direction is known, from pin to pin of the rocker)

(iii) Crank Force (From crank pin towards intersection of above two forces at 'M')

The direction of the first two forces is well known. The direction of the third force is to be obtained from the intersection of the first two forces (intersecting at M) which is explained in the following section.

4.1 Direction of Crank Force acting on coupler:

Since the tension in the rocker is along the line joining the pins at both ends of the rocker and the reaction force of the grabbed object is taken along its horizontal axis, these line of action of forces intersect at a point M. Also, their resultant is balanced by the crank force in order to achieve static equilibrium, according to S.S. Ratan [10]. Thus, the line of action of all three forces,which passes through M, are known to us.

The crank is run by servo motor SG 90 whose torque is 20KgF-mm at 5V DC power supply. For this configuration, the crank force can be calculated as 4.14 Kg-F. However, this crank force is not constant and will depend on perpendicular distance between line of action of crank force and the crank shaft of motor. When the fingers are fully closed, this distance is 4.83mm.

The vector diagram (Figure 4.1.1) for all three acting forces can be drawn. For convenience, the scale chosen is 1 Kg = 25mm and to achieve accuracy, all the diagrams are drawn on the AutoCad 2016.

The vector diagram is a closed loop with arrow head in the same sense (clockwise or counter-clockwise) which represents the static equilibrium of the finger subjected to three forces. In the figure below, they are observed to be counter-clockwise sense with the values measured as 103.5 mm (crank force), 11.06 mm (jaw force) and 110.42 mm (tension in Rocker). On dividing these values by the scale factor of 25 mm is to 1 kg, we get the values as 4.14 KgF, 0.442 KgF and 4.2 KgF respectively.

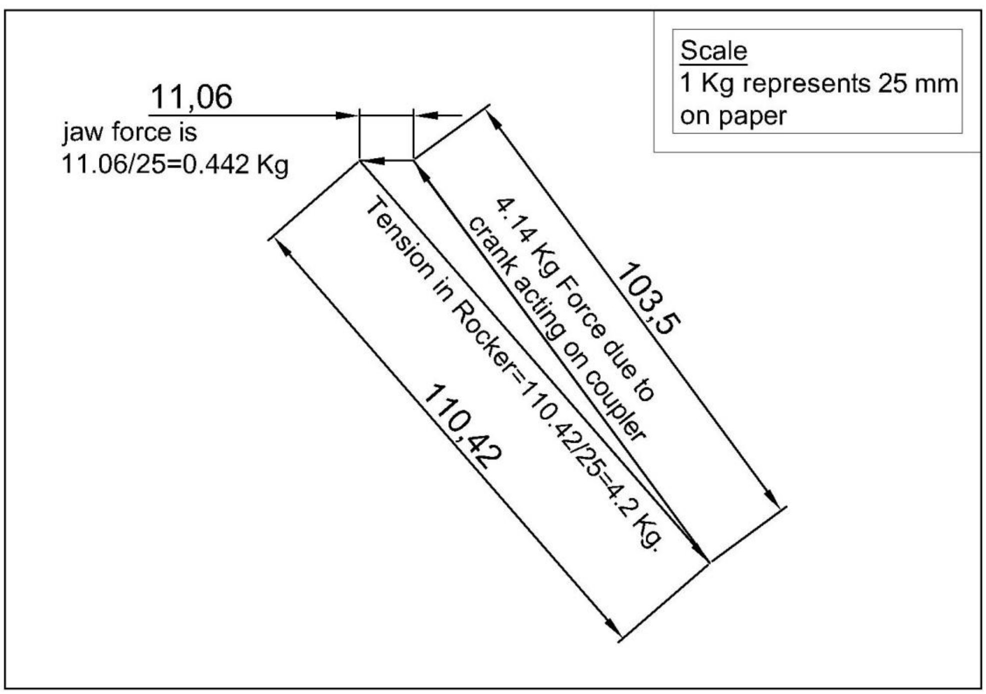

Figure 4.1.1 Force *Vector Diagram for fingers in fully closed position*

To draw vector polygon for the above configuration, first the crank force measuring 103.5mm with its direction is drawn and then, the direction of other two vectors are to be drawn such that we get a closed polygon, as shown by the Figure 4.1.1.For better understanding, same analysis is done for two more configurations at crank positions of 30° and 90°(Figure 4.1.2 and 4.1.3).

Few assumptions are considered while drawing vector polygon that is, the friction of pin joints are neglected and the forces are considered at a single point on the finger, so as to get the graph for variation of force at different positions of crank. Hence, the values obtained may vary if the point of application of force considered here is changed. However, the nature of graphs obtained in all the cases will not show much deviation.

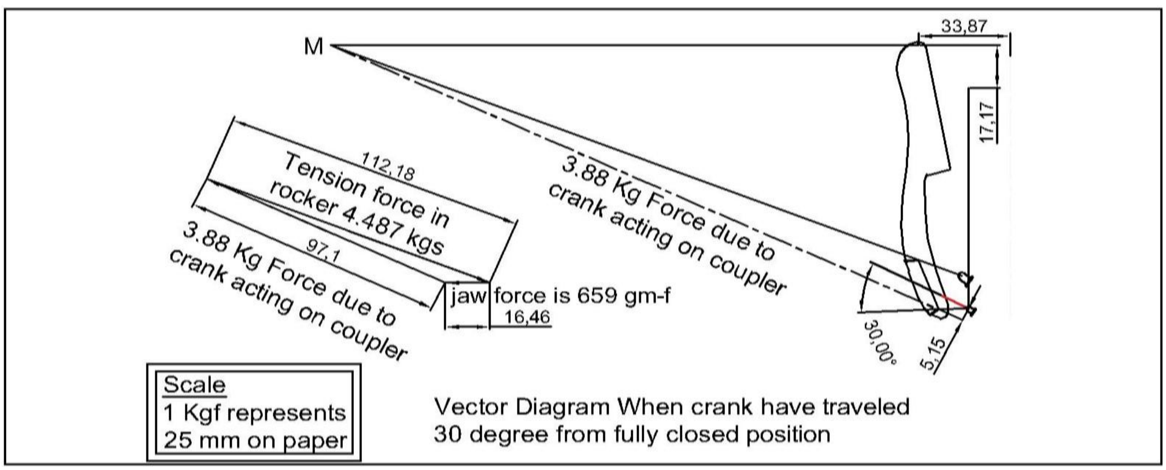

Figure 4.1.3 *Vector Polygon when the Crank Angle is 30° from its initial position*

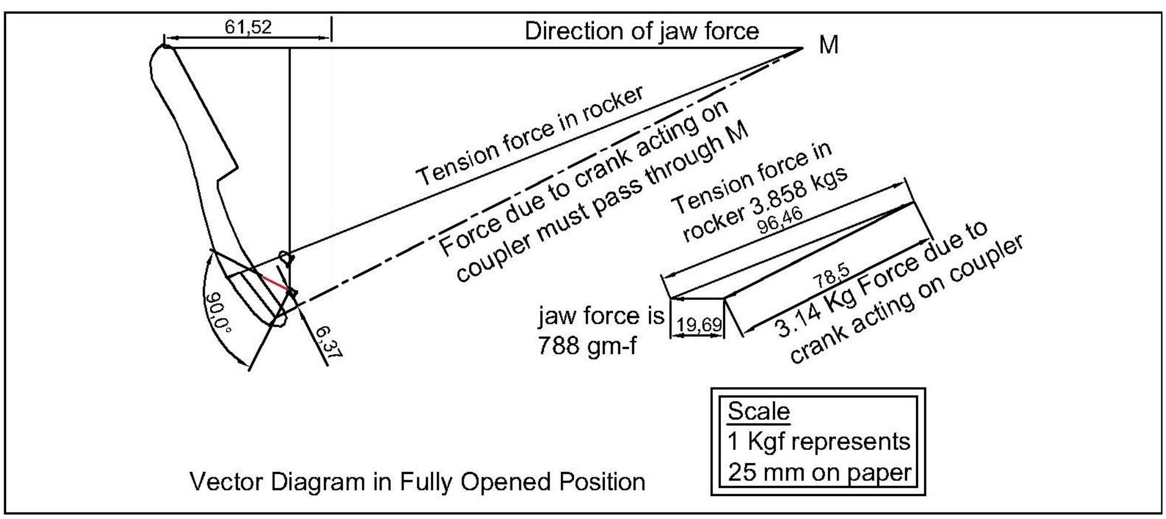

Figure 4.1.4 *Vector Polygon when the Crank Angle is 90° from its initial position*

5. Results and Analysis

5.1 Angular Displacement of Rocker and Coupler

According to the kinematics discussed in the Section 3.2, two tables (Table 5.1.1and Table 5.1.2) are drawn that shows the angle turned by rocker and the coupler (finger) of the gripper corresponding to crank angle for every 5° of crank motion. From the values of the table, a graph has been plotted as shown by Figure 5.1.1, which represents the angular displacement of rocker and coupler. Also, the angular velocity and further angular acceleration of rocker and coupler can be derived from these values by plotting the change of slope of these values.

Table 5.1.1 Angles turned by rocker and coupler corresponding to crank movement from 0° to 45°

Crank Angle	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**
Rocker Angle	0	4.91	9.62	14.17	18.59	22.89	27.09	31.20	35.22	39.15
Coupler Angle	0	1.81	3.48	5.07	6.60	8.08	9.53	10.97	12.41	13.85

Table 5.1.2 Angles turned by rocker and coupler corresponding to crank movement from 45° to 90°

Crank Angle	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**86.8**
Rocker Angle	39.15	43.00	46.76	56.44	54.04	57.55	60.97	60.30	67.45	70.60
Coupler Angle	13.85	15.31	16.78	18.27	19.80	21.37	22.97	24.62	26.37	28.12

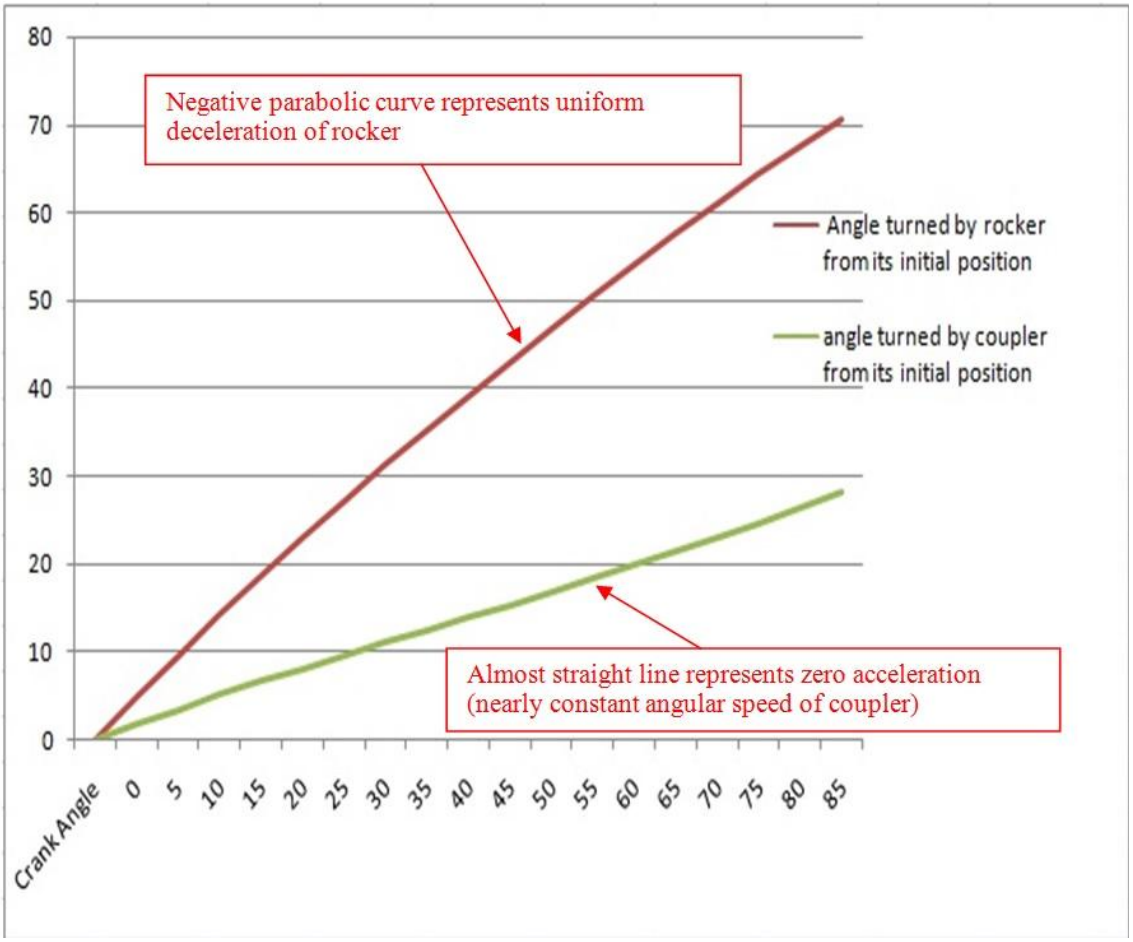

Figure 5.1.1 *Angular Movement of Rocker and Coupler corresponding to Crank Angle*

5.2 Rate of Change of Angular Displacement of Rocker and Coupler

By subtracting preceding values from the current values of Table 5.1.1 and 5.1.2, we get the rate of change of angles of rocker and coupler for every 5° interval of crank angle. These values are shown in Table 5.2.1 and 5.2.2. When these are plotted on graph, as shown by Figure 5.2.1, it represents the change of angular speed of the rocker and the coupler only with a condition that crank travels at a uniform angular speed.

Table 5.2.1 Rate of change of Angle turned by rocker and coupler with crank movement from 0° to 45°

Crank	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**

Angle									
Rocker Angle	0	4.91	4.71	4.55	4.42	4.3	4.2	4.11	4.02	3.93
Coupler Angle	0	1.81	1.67	1.59	1.53	1.48	1.45	1.44	1.44	1.44

Table 5.2.2 Rate of change of Angle turned by rocker and coupler with crank movement from 45° to 90°

Crank Angle	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**86.8**
Rocker Angle	3.93	3.85	3.76	3.68	3.6	3.51	3.42	3.33	3.15	3.15
Coupler Angle	1.44	1.46	1.47	1.49	1.53	1.57	1.6	1.65	1.75	1.75

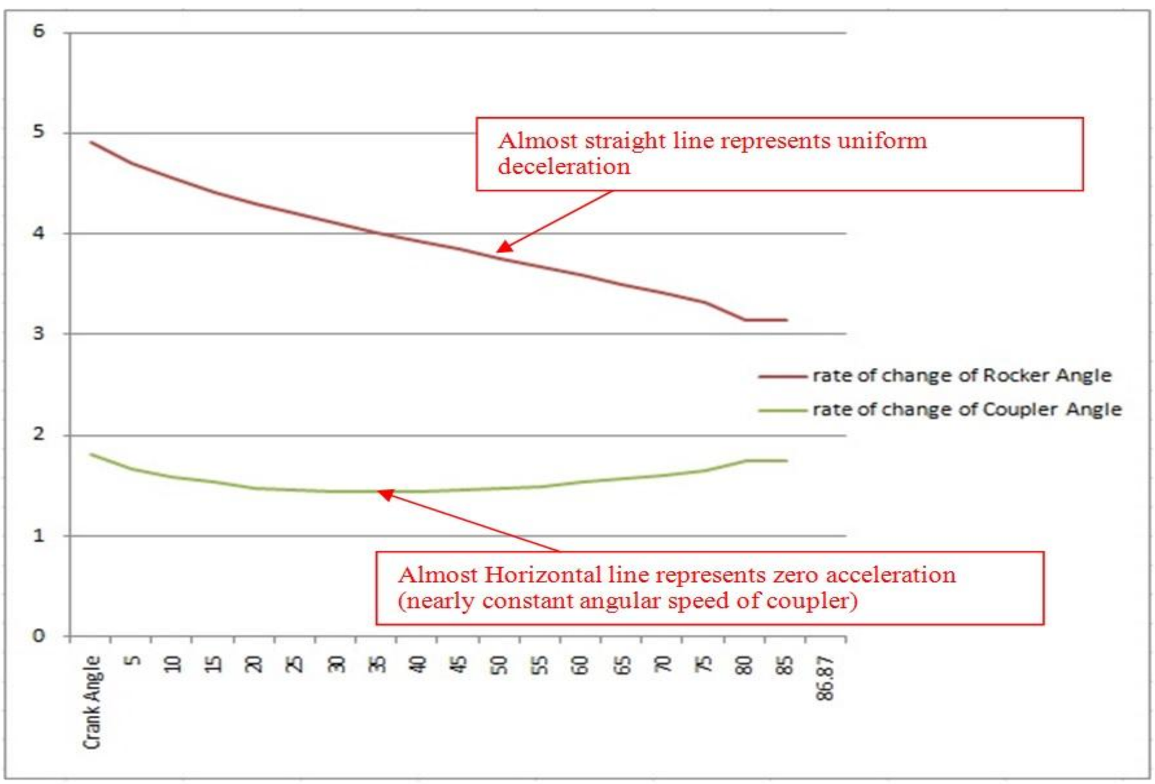

Figure 5.2.1 *Rate of change of angular movement of Rocker and Coupler corresponding to Crank Angle*

5.3 Gripper Force

As discussed in the Chapter 4, gripper force, tension in the rocker and the crank force are obtained from the force vector diagram for every 5° of crank motion. The values for the same are mentioned in Table 5.3.1 and Table 5.3.2. Also, the graph corresponding to the same values shows the variation in the gripper force (Figure 5.3.1).

Table 5.3.1 Forces acting on moving links of mechanism when crank is moved from 0° to 45°

Crank Angle	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**
Crank Force Transmitted to coupler	4.14	4.12	4.08	4.03	3.98	3.93	3.88	3.83	3.78	3.78
Tension in Rocker	4.42	4.46	4.47	4.48	4.48	4.48	4.49	4.48	4.47	4.45
Gripper force	0.44	0.49	0.53	0.56	0.60	0.63	0.66	0.69	0.71	0.73

Table 5.3.2 Forces acting on moving links of mechanism when crank is moved from 45° to 90°

Crank Angle	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**86.8**
Crank Force transmitted to coupler	3.78	3.68	3.62	3.57	3.51	3.44	3.37	3.3	3.22	3.14
Tension in Rocker	4.45	4.42	4.39	4.34	4.3	4.23	4.15	4.06	3.96	3.86
Gripper force	0.73	0.75	0.77	0.78	0.79	0.80	.80	0.80	0.79	0.79

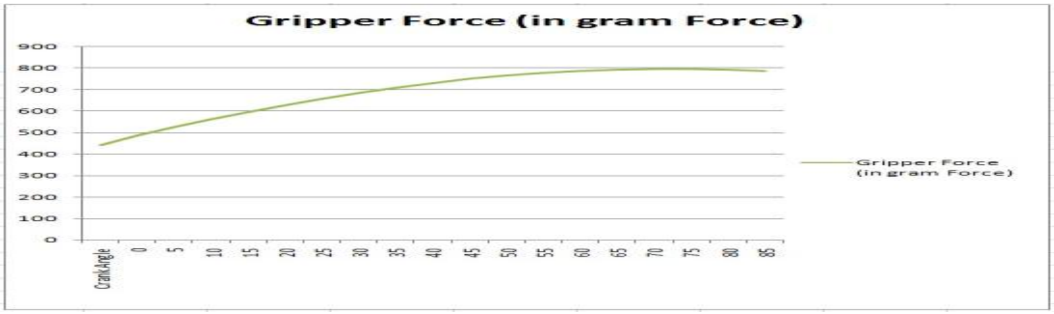

Figure 5.3.1 *Crank angle vs Gripper force*

5.4 Load Testing Results

This light weight gripper was provided with sufficient thickness at critical sections so as to bear bending, shearing and tensile forces for 4 Kg Force of external load on fingers. When tested with static load of 2 kg, no deformation was observed as shown in the Figure 5.4.1.

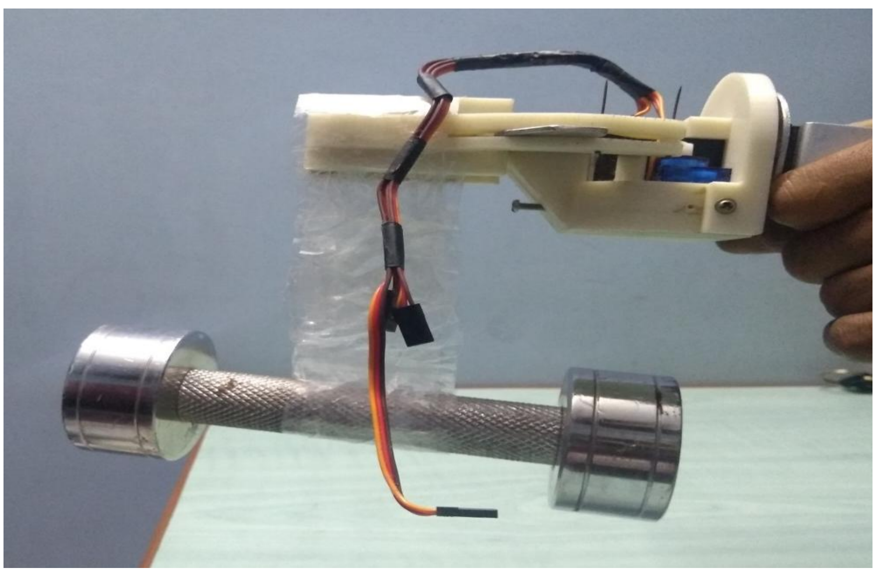

Figure 5.4.1 *Light weight gripper bearing 2 kg weight*

6. Conclusion

After design and analysis, a light weight gripper is developed whose total weight is 212 grams of which 85 grams is the total weight of three motors. Maximum tension in coupler and rocker are calculated as 4.14 Kg-Force and 4.45 Kg-Force respectively. The weight of the object to be lifted depends on the coefficient of friction and the minimum gripper force, which is 440 gram-Force per finger. In future, the shape of the gripper can be optimised for weight reduction and also, the fingers can be modified for special objects.

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