Design of a Universal Robot End-effector for Straight-line Pick-up Motion

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Abstract

This paper describes a capstone design project in developing an end-effector for robotic arm that is capable of grasping objects of varying sizes. The design parameters are as follows. The center point of end-effector should remain as close as possible to the same location, i.e. a straight-line path, over the range of gripper motion. The selected size and shape of the grasped object are cylinders ranging from 50 mm to 300 mm in diameter. The desired clamping force is 625 N per jaw when the gripper is at its maximum open position. The force required to drive this mechanism is provided by electricity and a maximum lift mass is 70 Kg. This project gives students an appreciation for powerful the computer-aided engineering method can be in performing mechanism design and analysis. Additionally, the students gain throughout understanding of topics in mechanism design, stress analysis and manufacturing application as well as have the opportunity to involve a real industrial project.

1. Introduction

As customers demand a wider variety of product choices and even more frequent product introductions, the need for flexible robotic tooling has been greater for material handling during manufacturing process. This capstone design project, defined as one semester work, is to develop an end-effector for robotic arm that is capable of grasping objects of varying sizes. The design parameters are as follows. The center point of end-effector should remain as close as possible to the same location, i.e. a straight-line path, over the range of gripper motion. The selected size and shape of the grasped object are cylinders ranging from 50 mm to 300 mm in diameter. The desired clamping force is 625 N per jaw when the gripper is at its maximum open position. In addition, it is desired that the force required to drive this mechanism is provided by electricity and a maximum lift mass is 70 Kg.

Commercially available robotic grippers can be separated into three general categories. The first category is a pneumatic cylinder that drives a toggle mechanism which produces the clamping motion. The second category is an electric motor driving a power screw which in turn drives a toggle mechanism. In this case, the toggle mechanism also provides the clamping motion. The third category is an electric motor driving a power screw which slides a vice shape mechanism. This vice creates the clamping motion. The disadvantage of using pneumatic cylinder is that force produced by a pneumatic cylinder is not generated immediately, because the pneumatic cylinder requires some time to settle down after it reaches closed position. The shortcoming of using toggle mechanism to create the clamping motion is a limit factor for gripper design. A toggle mechanism by definition is used whenever a large force is required through a short distance [1]. This fact precludes a toggle mechanism from being used over large variations in size. Based on the above discussion, this project utilizes an electric motor to drive a power screw which in turn drives a toggle mechanism. Power screw is used to convert rotary motion of either a nut or screw to relatively slow linear motion along the screw axis. Power screw also produces large mechanical advantage [2].

To perform a straight-line pick-up motion, the Scott Russell straight-line mechanism might be applied. A standard Scott Russell straight-line mechanism provides exact straight-line motion of point E, as shown in Fig. 1(a) [3, 4]. A variation of this mechanism is shown in Fig. 1(b), where the slider is replaced by crank BD. In this linkage, point E has approximate straight-line motion. The problem with using these mechanisms is the placement of the pivot which is directly in line with the clamping motion of the devise. This pivot would be in the way of any object other than one shape like a donut. Therefore a modified Scott Russell straight-line mechanism is developed to overcome this geometrical restrain of object to be picked up.

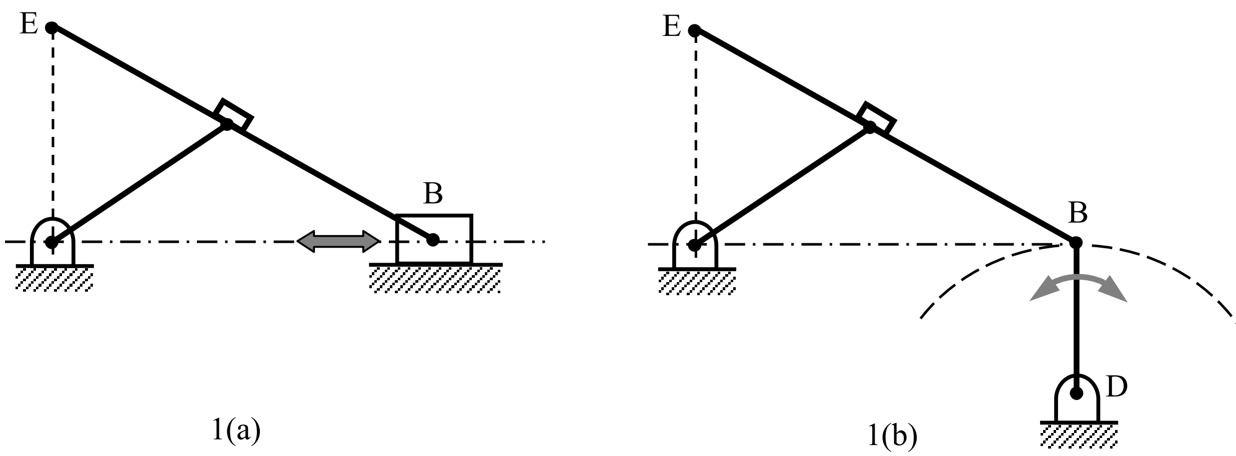


Figure 1. Standard Scott Russell straight-line mechanism

In this design project, the gripper of robot end-effector has three jaws which move closed and clamp on an object in the center point of end-effector. This method of picking up and clamping round objects of different sizes is the most stable jaw configuration [5]. To keep the center point of end-effector as close as possible to a straight-line path over the range of gripper motion, a modified Scott Russell straight-line mechanism is used in each jaw.

This paper emphasizes the design of a modified Scott Russell straight-line motion mechanism, clamping force computation, and maximum lift mass. A commercial computer-aided mechanism design software, WorkingModel 2D [6], was introduced to students. This software is mainly used in motion path generation.

2. Modified Scott Russell Straight-line Motion Mechanism

Figure 2 shows a standard Scott Russell straight-line mechanism with an additional point D located 85 mm farther out of point E. Point E represents the position of center point of the clamp jaw, which creates a true Scott Russell straight-line path. However the placement of the pivot point (point C) is directly in line with the clamping motion of the devise. This pivot point would be in the way of any object other than one shape like a donut. Additional problem here is the sweeping path of point D. Based on simulation result, point D sweeps through a maximum value of 7.65 mm over the total devise range of motion. To accommodate the somewhat straight-line path and required clamping force, a modified Scott Russell straight-line mechanism is developed.

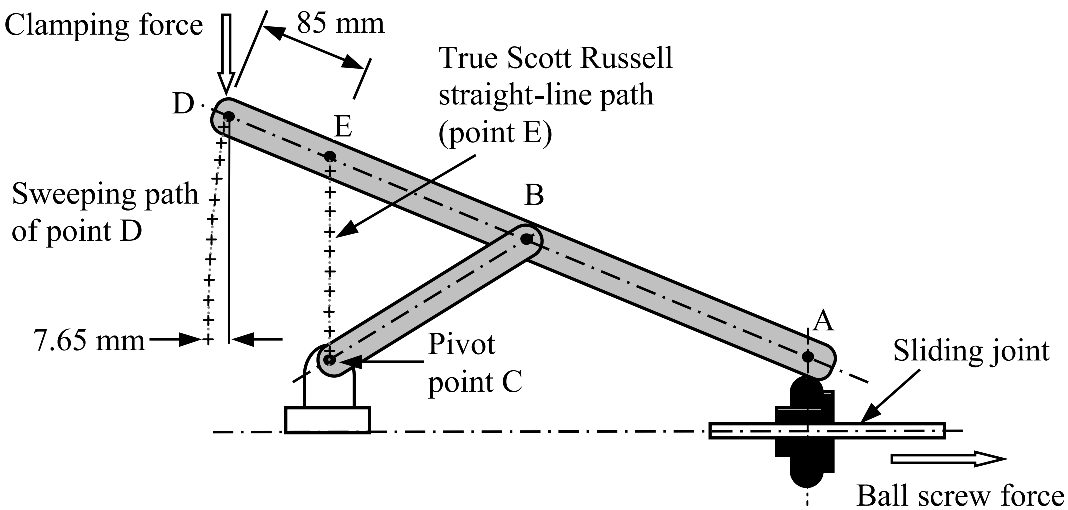


Figure 2. Standard Scott Russell straight-line mechanism with additional point

One goal of this project is to keep the clamping center point as close as possible to the same location over the range of motion of the gripper. To improve the condition illustrated in Fig. 2, the pivot at point C is moved inward 20 mm. Figure 3 illustrates a modified Scott Russell mechanism where point C is moved down flattened out the path of point D. The size of object to be grasped affects the sweeping offset distance on point D. Since the selected size and shape of the grasped object are cylinders ranging from 50 mm to 300 mm in diameter, the distance from the ball screw axis to the top face of the object is radius of object to be grasped (25 to 150 mm). Table 1 shows the relationship between the sweeping offset distance of point D and object size. The maximum sweep offset distance of point D is 2.28 mm.

Three jaws are fanned out 120 degrees from one another and connected at slider joints. These modified Scott Russell linkages are driven at their sliding joints with a power screw which provides force multiplication. A servo electric motor provides the rotating motion required by the power screw.

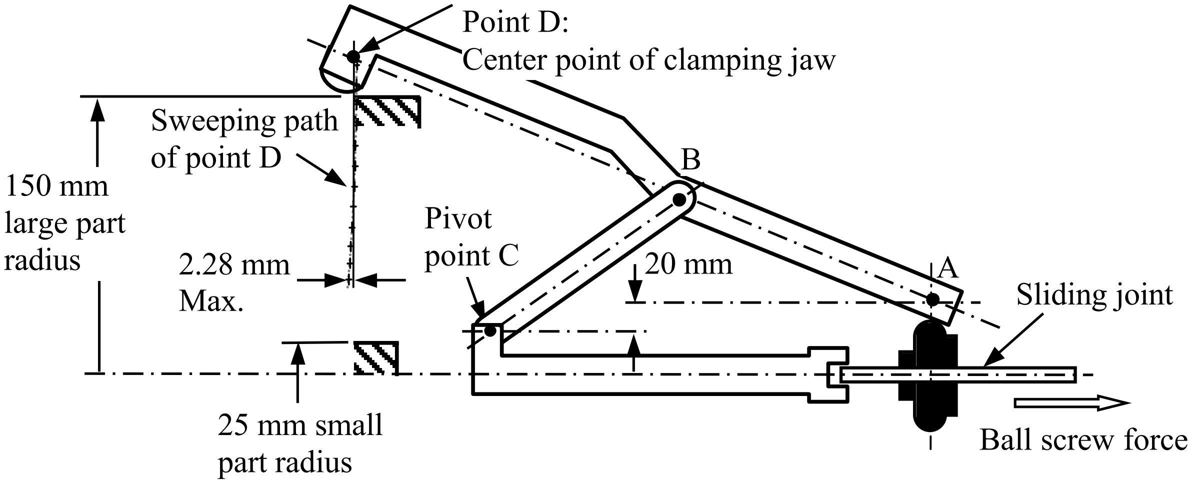


Figure 3. Modified Scott Russell straight-line mechanism

Table 1. Sweeping offset distance of different sizes of objects

Object size (mm)	80	100	120	140	160	180	200	220	240	260	280	300
Sweeping offset (mm)	0.66	1.03	1.36	1.64	1.86	2.04	2.17	2.23	2.28	2.25	2.17	2.06

3. Clamping Force Computation

This section presents the computation of clamping force. Figure 4 illustrates the free body diagram of links ABD and BC. Link BC is a two-force link: the force at point C is the same magnitude as point B and parallel to line BC. Although the force created by ball screw is not along line AC, only the force component along line AC was taken into calculation in order to simplify the computation. All calculations are made starting with the gripper closed. The free body diagram shows the gripper in the wide-open position which serves as a check for calculation. The final set of calculation should match the graphical dimensions shown in Fig. 4. Load calculations are made at each increment as if the gripper closed on each size object. The assumption is that maximum clamping force on the gripper occurs when the gripper closed on an object. The final force calculation takes the component of the clamping force square to the ball screw, which is the true clamping force. Spreadsheet is created to make the computation. The following equations are inputs of the spreadsheet.

F_{BS} = 1349 N, Force per arm (1)
I = from 0 through 27 mm, Increment of ball screw stroke (2)
$\alpha = \tan^{-1}(20/(298.2-I))$, Angle α (3)
$F_{AC} = F_{BS} \times \cos\alpha$, Ball screw force along line AC (4)
$\beta = \cos^{-1}(AC/2)\times150$, Angle β (5)
$F_C = F_{AC} \times \tan\beta$, Clamping force normal to line AC (6)
$F_{BC} = F_{AC} \times \cos\beta$, Force along link BC (7)

F_{BCX} = -F_{AC}, F_{BCX} is component of F_{BC} in X-direction (8)
F_{BCY} = -F_C, F_{BCY} is component of F_{BC} in Y-direction (9)
$F_{CBS} = F_C \times \cos\alpha$, Component of clamping force normal to ball screw (10)

F_{BS} is calculated based on ball screw specification, as illustrated in Esq. (11) and (12).
$F_B = 2\pi T\eta/L$ (11)
$F_{BS} = F_B$/Number of arm (12)

Where F_B is axial force in ball screw (N), L is lead of ball screw (m), T is load torque (N-m), and η is ball screw efficiency. In this design, $\eta = 0.95$, L = 0.005 m, and T = 3.39 N-m, they are provided by ball screw manufacturer [7]. Therefore, F_B = 4047 N and with 3 arms F_{BS} = 1349 N.

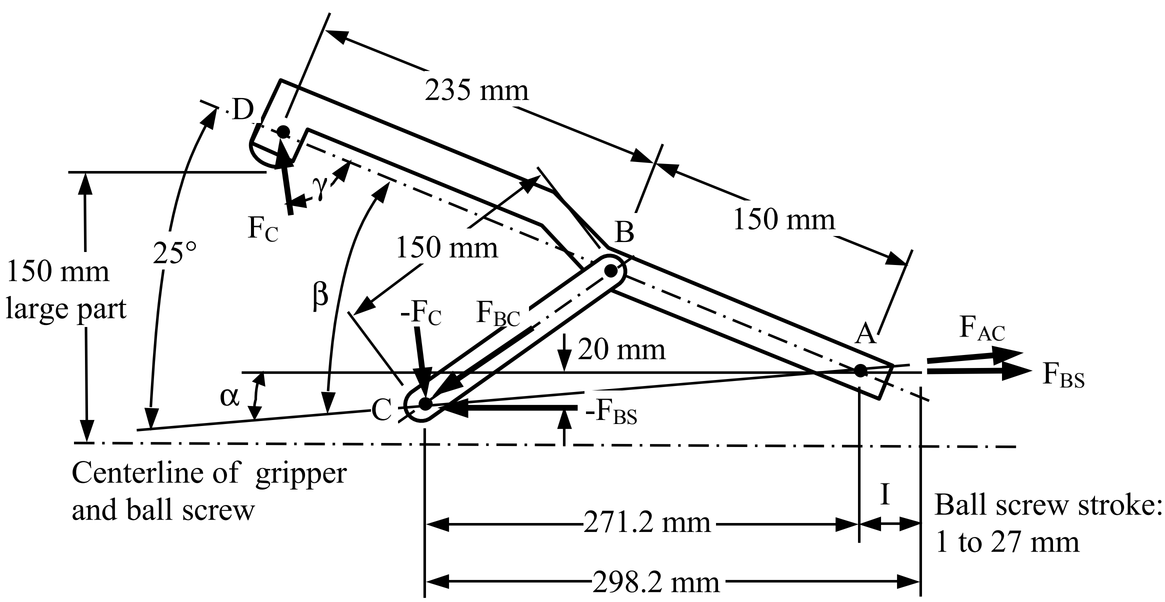


Figure 4. Free body diagram of links

Clamping force values calculated from spreadsheet are shown in Table 2. Figure 5 presents the relationship between the increment along the ball screw and the clamping force. As the ball screw reaches its maximum stroke (27 mm), the maximum clamping force is obtained (625 N).

4. Gripper Lift Weight Computation

The actual maximum weight that gripper can lift depends on the clamping force of gripper and material the lifted object is made from. The frictional force between the object and the gripper jaws is what holds the object against gravity. Table 3 shows the maximum weight can be lifted for different types of materials. The maximum clamping force of 625 N, safety factor of 2, and end-effector with 3 arms/jaws are used. The coefficients of frictions are from [8].

Table 2. Simulation results of clamping forces

Ball screw stroke increment (mm)	Angle α (degree)	Length of AC (mm)	Angle β (degree)	F_{AC} (N)	F_{BC} (N)	F_C: Clamping force (N)
0	3.8	298.9	5.0	1346	1341	117
1	3.8	297.9	6.8	1346	1336	161
2	3.9	296.9	8.3	1346	1332	195
3	3.9	295.9	9.5	1346	1327	225
4	3.9	294.9	10.6	1346	1323	251
5	3.9	293.9	11.6	1346	1318	275
6	3.9	292.9	12.5	1346	1314	298
7	3.9	291.9	13.4	1346	1309	319
8	3.9	290.9	14.2	1346	1305	339
9	4.0	289.9	14.9	1346	1300	358
10	4.0	288.9	15.6	1346	1296	376
11	4.0	287.9	16.3	1346	1291	393
12	4.0	286.9	17.0	1346	1287	410
13	4.0	285.9	17.6	1346	1282	427
14	4.0	284.9	18.3	1346	1278	443
15	4.0	283.9	18.9	1346	1273	458
16	4.1	282.9	19.4	1346	1269	474
17	4.1	281.9	20.0	1346	1264	488
18	4.1	280.9	20.5	1346	1260	503
19	4.1	279.9	21.1	1346	1255	517
20	4.1	278.9	21.6	1346	1251	532
21	4.1	277.9	22.1	1346	1246	545
22	4.1	276.9	22.6	1345	1242	559
23	4.2	275.9	23.1	1345	1237	573
24	4.2	274.9	23.6	1345	1233	586
25	4.2	273.9	24.1	1345	1228	599
26	4.2	272.9	24.5	1345	1224	612
27	4.2	271.9	25.0	1345	1219	625

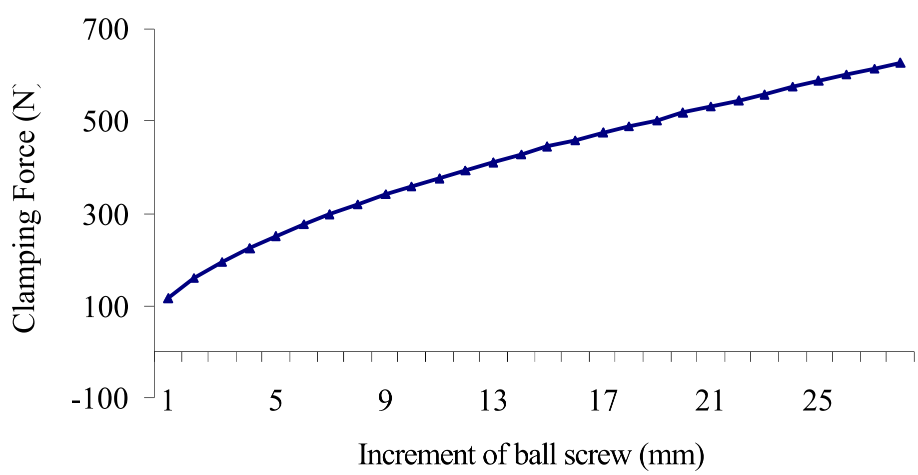


Figure 5. Graph of clamping force vs. ball screw stroke increment

Table 3. Maximum lift weight of different types of materials

Material	Coefficient of friction	F_C Clamping force (N)	Friction force per arm (N)	Factor of safety	Maximum lift weight per arm (N)	Total lift weight (N)	Total lift mass (Kg)
Steel	0.74	625	462	2	231	694	70.8
Aluminum	0.61	625	381	2	190	572	58.3
Copper	0.53	625	331	2	166	497	50.7
Brass	0.51	625	319	2	159	478	48.8
Teflon	0.04	625	25	2	12	38	3.8

5. Stress Analysis of Link

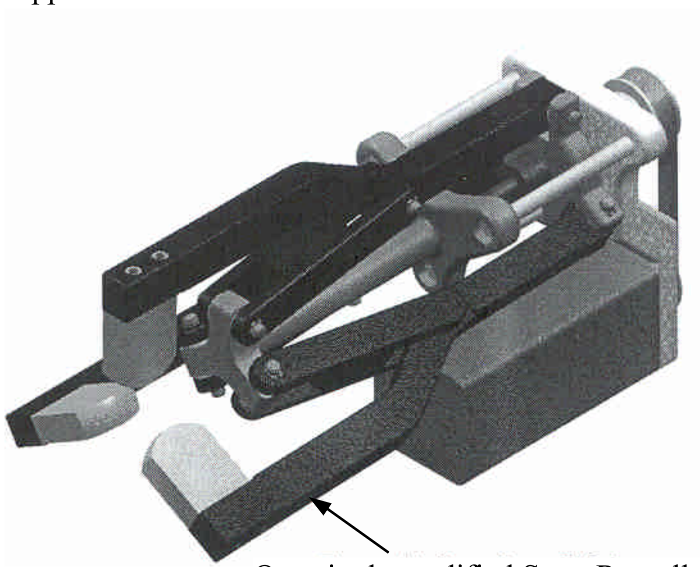
For accurate results the complex shape of link ABD (referring to Fig. 4) would require stress calculations on FEA (Finite Element Analysis) software, however the application of FEA is beyond the scope of this project. The students perform stress analyses based on their knowledge learned from previous courses: mechanics of materials and machine components design. All links are made of aluminum material 6061-T651 with 96 MPa endurance limit [9]. The stress is calculated at point B using force F_C and link BD, since point B is the point of highest stress. The maximum magnitude of Fc is when the gripper opens to its maximum position, which results in maximum tensile stress at point B on the bottom side of link BD.

$F_{BDT} = F_C \times \cos\gamma$, Tensional component (along BD) of F_C (13)
$F_{BDN} = F_C \times \sin\gamma$, Normal component (perpendicular to BD) of F_C (14)
$\sigma_T = F_{BDT}/A$, Tensile stress due to axial force (15)
$\sigma_B = (F_{BDN} \times 235)y/I$, Tensile stress due to bending moment (16)
$\sigma_R = \sigma_T + \sigma_B$, Resultant stress at the bottom side of BD link (17)

where γ is angle between force F_C and link BD (referring to Fig. 4), A and I are cross-section area and moment of inertia at point B, respectively. The maximum resultant stress is calculated as 7 MPa (with $F_C = 625$ N, $\gamma = 69.2°$, $A = 240$ mm^2, and $I = 2.96 \times 10^5$ mm^4), which is less than the endurance limit of the material. Therefore stress in the link ABD is not a concern for this mechanism. The deflection of each link could affect the pick-up motion, lift weight and size of part. This deflection analysis will be carried out by other capstone design project.

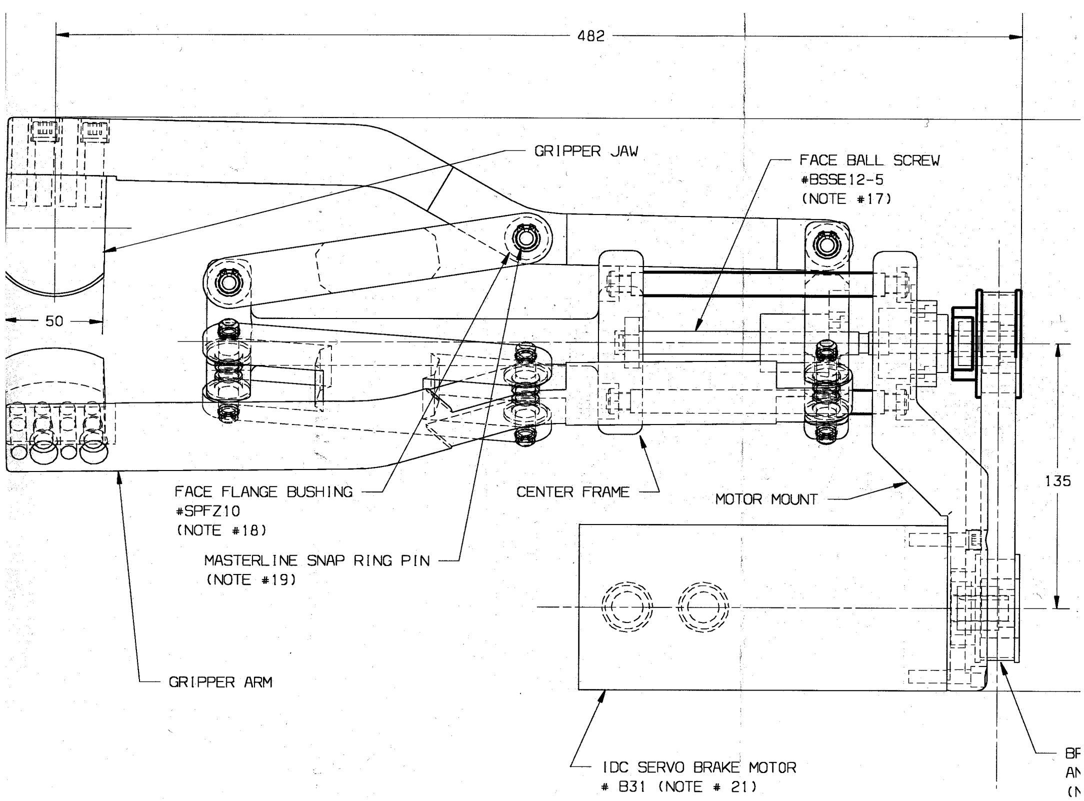
6. Assembly of End-effector and its Application

Figure 6(a) illustrates a solid model of designed gripper with three modified Scott Russell straight-line mechanisms and Fig. 6(b) shows an assembly layout. Three jaws are fanned out 120 degrees from one another and connected at their slider joints. This gripper is well suited for use with a two-axis gantry robot which picks up parts of different sizes from a conveyor and place the parts on an inspection table. The students did not build a physical full-size or scaled-size of mechanism, however they performed detail design, components selection, analysis, and engineering drawings creation of detail part and assembly. Based on the result of this project, a prototype of straight-line pick-up motion gripper has been implemented in production line of one automotive supplier.



One single modified Scott Russell straight-line mechanism as shown in Fig. 3

(a) Solid model of three modified Scott Russell straight-line mechanisms



(b) Assembly layout of designed mechanism

Figure 6. Gripper assembly of three modified Scott Russell straight-line mechanisms

7. Conclusions

This paper describes a capstone design project in developing an end-effector for robotic arm that is capable of grasping objects of varying sizes. A modified Scott Russell mechanism was developed to perform straight-line pick-up motion. The center point of three jaws stays relatively constant over the grippers' range of motion. The clamping force profile of the gripper is designed so that the maximum clamping force is generated as the object is the largest. The maximum lift weights from different types of materials are also computed. All these design parameters meet the target values. This project gives students an appreciation for powerful the computer-aided engineering method can be in performing mechanism design and analysis. Additionally, this design project integrates the students' knowledge of mechanism design, stress analysis and manufacturing application. The students gain throughout understanding of these topics and have the opportunity to involve a real industrial project.

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Biography

Y. GENE LIAO, currently an assistant professor at the Wayne State University, received his B.S.M.E. from National Central University, Taiwan, M.S.M.E. from the University of Texas, Mechanical Engineer from Columbia University, and the Doctor of Engineering degree from the University of Michigan, Ann Arbor. His research and teaching interests are in the areas of mechanical design, multibody dynamics, and CAE applications in manufacturing. He has 15 years of industrial practice from automotive sector prior to becoming a faculty member.