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THE DESIGN OF AN ANIMATRONIC ARM

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Abstract - *This project deals with the design of an Animatronic Arm. This project isa part of a project that makes an interactiverobot. There are a total of three teams, the other two are dealing with the locomotion part and the control system part. Our duty was to design an "Animatronic Arm". This is not a replica of a human hand but is an adaptation. Wetriedto give themaximum degrees of freedom to the Animatronic Arm within our constraints. Thedegrees of freedom are of thefingers, wrists motion, elbow motion, the up and down, and the sideways motionsof the total arm (that is, at the shoulder). A total of elevendegrees of freedom have been achievedunder the design. We used gear systems, servo motors, and other parameters to achieve our target. We completed this project by identifying the better and effective mechanisms to bringout the desireddegrees of freedom we needed. The final designof the arm matched withthe total robot design in termsof total weight and hindrance.*

***Key Words*: Animatronic arm, Degrees of Freedom, biomimicking**

1. INTRODUCTION

The human arm including the shoulder, elbow, wrist joints, and exclusion scapular motion has 7 Degrees of Freedom (DOF) while positioning the wrist in space and orientating the palm is a task that requires 6 DOF. As such it includes one more DOF than is needed to complete the task. Given the redundant nature of the arm, multiple arm configurations can be used to complete a task. Bionic arms are intuitive artificial limbs that use cutting-edge technology to connect with the body. They use special sensors to detect and convert naturally generated electrical signals from muscles into movement. Bionic arms are custom-built to fit the residual limb, and their sensors are calibrated to the user's strongest muscle signals. A lot goes into creating a bionic prosthetic, and the technology has improved significantly over the years, from lightweight and sturdy materials to state-of-the-art electronics. A bionic arm is so close to a normal human arm. Thus, it is very complicated and costly to make a bionic arm.

Our design is very much cost-effective than a bionic hand, within this cost constraint, we tried to propose an effective design. The simplicity and usage of gears, servo motors, strings, springs, etc... enabled us to make an Animatronic Arm. The gears along with the servo motors could bring needed degrees of freedom to the design. It is very important to not cause any hindrance or trouble to the total robot design. Hence, we kept the constraints in our mind throughout the designing process. A sufficient electrical system is needed for the functioning ofthe Animatronic Arm. Thus, by combining the results of our design and the inputs from the control system team the arm can be completed.

1.1 OBJECTIVE

In this new world of advanced technological revolutions, the fast-forward answer which creeps into the mind is remote actuation. Remote actuation or in terms ofrobotics the most controversial term- the master and the slave. The master is an actuation signal sent by us in a safe habitation area while the slave accepts and reacts to the signal at the remote location. An artificial (any DOF) gripper, biomimicking the human hand is thus called the Animatronics Hand. Animatronics in "Animatronic Hand" refers to anything animal-like with mechatronics integrated. One of its biggest advantages is replacing any humans working in hazardous environments. The hand, fixed to a rolling base makes transportation easier while adding additional DOF.

What we attempt, has been attempted, many times before but what makes this different, is that we learn from the mistakes to build something better. As in the words of Stephen William Hawking, "We stand on the shoulders of giants.". Our objective is to propose a simplistic animatronic arm design that has essential degrees of freedom.

2. DESIGN METHODS

2.1 PALM AND FINGERS

The basic length for the palmand the fingers is ofthe normal adult human dimensions. The servo motors are used to pull the strings which are connected to the springs. The PET along with the springs are acting as the fingers. The specifications of the servo motors, strings, and springs are selected based on the torque calculations. The concept used here is the static load concept. The retire materials are designed based on the assumption that the arm will pick a weight of 40 N or a mass of 4 kg. PET (Polyethylene terephthalate) to construct the finger parts**.**

Fig-1: The concept of finger construction and design

When assembling the fingers, the parts were oriented correctly before gluing. Also, it is important to re-drill the holes on the finger parts so the 3mmscrews will act as hinge pins without causing friction. Then the part could be connected using a string and screws. The strings join the servo motors and the fingers. The servomotors are placed in a servo bed made of PET (3D printing material). A total of five servo motors are needed here to pull the five fingers. Hence, here there are five degrees of freedom.

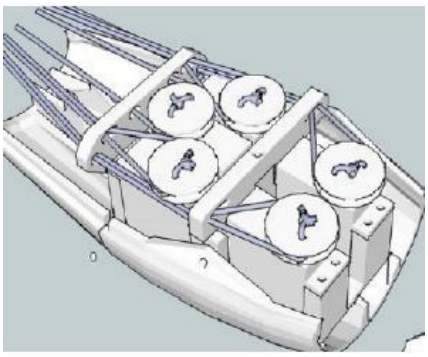

Fig-2: The conceptof placement of servo motors.

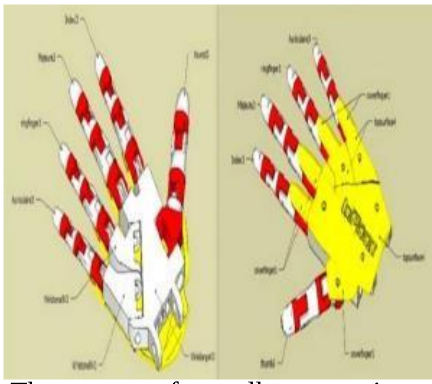

Fig-3: The concept of overall construction of the palm and the fingers.

2.2 FOREARM AND UPPER ARM

The forearm and upper arm rods are made of AISI 4130 alloy steel and are of hollow square cross-section. Obtaining a relationship between breadth and thickness, the needed dimensions could be found out. Later the mass and weight of arm rods, sheet metals used for covering the rods have been found. The mass ofthe gears and the extra arrangements are also considered along the project calculations.

Fig-4: Parts of a human arm.

2.3 GEAR SYSTEM

Calculating the torque of every part understudy, the corresponding gears ratio could be found. The servo motor should be selected carefully, as it should match the total design. And the weight ofthe servos should also fall under the design constraints.

THE OVERVIEWOF FIRST AND SECOND ITERATION

We had a vague idea about how the design should be (through the preliminary drawings). We started with estimating the weight of sheet metal which coversthe arm. Later we calculated the dimensions of the forearm and upper arm steel rods. Now, the systems giving adequate degrees of freedom are added to the rods. The mass is calculated in each step (the masses of the added systems). This mass is important in calculating the forces for the gear selection. Then, the force and torque calculations have been made. Initially (in the first iteration), we had selected the pulley system. That is the piston, air compressor, andpulley system.

But the results of the first iteration (in the case of the mechanism used) were not satisfactory. The weight of the air compressor was too large to accommodate within the design. Hence, we omitted the pulley, piston, and air compressor mechanism. In the second iteration, the mechanismselected was of the gear systems. The calculated results were satisfactory to accommodate within the design. Hence, we completed the design using the gear systems. (The details are shown in the design and calculations section).

3. DESIGN CALCULATIONS

3.1 DESIGN OF THE FOREARM AND UPPER ARM RODS

- The length of the forearm and upper arm steel rods are of the normal human dimensions. The material used is AISI 4130 Alloy Steel Hollow Square Rod. The ultimate tensile strength, density, etc... used in the below equations are of AISI 4130 Alloy Steel. (Finding the breadth (b) and thickness (t) of the rods).

$$\rightarrow \sigma_{max} = \frac{Ultimate\ tensile\ stress}{factor\ of\ safety} = \frac{560\ Mpa}{2} \qquad ...(1)$$

$$Tensile\ bending\ stress\ (\sigma_b) = \frac{M_b \times c}{I} \qquad ...(2)$$

$$\rightarrow I = \frac{b^4}{12} - \left(\frac{(b-2t)^4}{12}\right) \qquad ...(3)$$

- We have, M=(Pl)/4= (4*10*200)/4=2000Nmm.…(4)
- Framing a relationship between breadth and thickness fromthe above given equations.
- From (2) and (3)

  $16b^3-96b^2+213.09b-256=0$

- Selecting values that validate the above expression and our rough dimensions. Thus, breadth (b) = 20 mm and thickness (t) = 2 mm. (Here, the design has been made considering the arm will picka mass of 4 kg). Thus, breadth and thicknessof the forearm and upper arm rods are 20 mm and 2 mm.

ROD AND SHEET METAL MASS

- Mass of forearm's sheet metal

$$Volume\ of\ the\ forearm's\ sheet\ metal = \pi(r_1 + r_2)(t)(l)$$

$$Volume = \pi(35 + 34)(1)(140) = 30347.785803\ mm^3$$

$$Mass = (Volume)(Density) = (30347.785)(8)(10^{-6})$$

$$Mass\ of\ the\ forearm's\ sheet\ metal = 0.2427\ Kg$$

- Mass of upper arm's sheet metal

$$Volume = \pi\ (50 + 49)(1)(140) = 43542.47\ mm^3$$

$$Mass = (Volume)(Density) = (43542.47)(8)(10^{-6})$$

Mass = 0.38 Kg

- Mass of forearm's rod

$$Volume = \pi\left(20^2 - 18^2\right)(1)(110) = 26263.71\ mm^3$$

$$Mass = (Volume)(Density) = (26263.71)(7.85)(10^{-6})$$

$$Mass\ of\ the\ forearm's\ steel\ rod = 0.206\ Kg$$

- Mass of upper arm's rod

$$Volume = \pi\left(20^2 - 18^2\right)(1)(140) = 33426.54583\ mm^3$$

$$Mass = (Volume)(Density) = (33426.54583)(7.85)(10^{-6})$$

$$Mass\ of\ the\ upper\ arm's\ steel\ rod = 0.262\ Kg$$

3.2 DESIGN OF THE PALM AND FINGERS

- The length of the palm is taken as that of a normal human palm. The length of the fingers is taken asthe same (75 mm) tomake the spring constant thesame.

$\rightarrow \mu \times N = 40$ Newton, $N -$ force acting on all five strings.

$\rightarrow N = 666.67\ N$

$\rightarrow$ Force acting on one string, $F = \frac{666.67}{5} = 133.33\ N$

$$\sigma_{max} = \frac{\text{Ultimate tensile strength of string material}}{\text{factor of safety}} = \frac{515\ Mpa}{2}$$

(the material is 304 stainless steel)

$$\sigma_{max} = \frac{4F}{\pi d^2}, \text{ d is the diameter of the string}$$

- Substituting the values to the above equation, we will get, d = 0.811 mm.

  → Minimum torque required to pull the string=F*10

  → The required torque= 13.334 Kg f cm

- For finding the spring constant, the length of the fingers is assumed to be 75mmand the spring travel is 90 degrees.

  Spring constant k= 50N/106mm

- Here, 50 N is the extra force generated from the used servo motor and 106 is the spring travel calculated from thePythagoras theorem.
- Hence, the spring constant = 0.0471698 N/mm

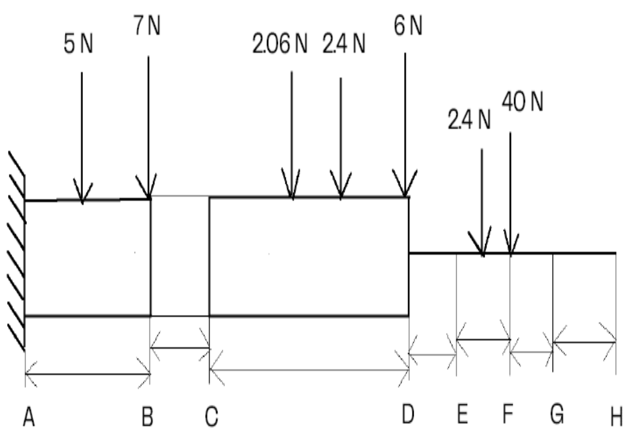

Fig-5: The forces acting on the whole arm. (This figure is used for the torque calculation.)

AB - Length of the upper arm (140 mm).

CD - Length of the forearm (110 mm).

BC - Allowance for the gear (25 mm).

DE - Allowance for the gear (30 mm).

FG - Distance to the center of the palm (70 mm). FH

- Length of the fingers (75 mm).

The eight of each element could easily be calculated from the mass.

3.3 DESIGN OF THE WRIST MOTION

Here, the application of zero torque is considered. And, a servo is selected accordingly to bring out the desired motion. Combining the results of gear ratios, we obtained from the first and second iteration. Taking the average, we will get a gear ratio of 2. Hence, the gears selected area of 23 mm in diameter. There are some other elements required for the wrist motion (explained in the methods section). The specification for those elements has been selected from a series of assumptions. Since the torque is zero here, the gear ratio is 1. A gear of appropriate dimensionis selected. This has been selected strictly based on the total geometry of the assembly.

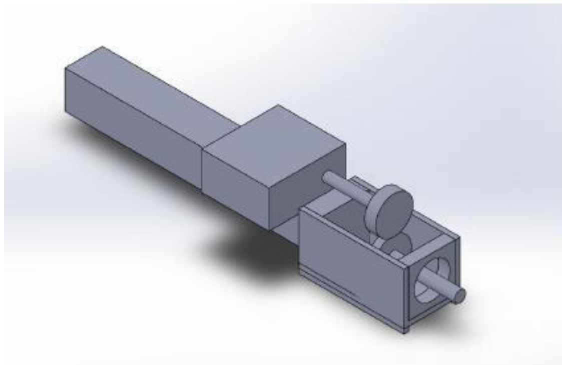

Fig-6: CAD model of the wrist motion.

The specification of the circular rod is selected by the geometry of the whole arrangement. Its job is to connect the forearm rod with that of the palm part. The servos are placed in the palm part. The circular rod should be inserted in between the servos and should forma connection between the forearm and palm. The bearing and the plates are al so selected based on the whole geometry. The material used for the plates and bearing is AISI 4130, which is capable of giving such good strength. Hence, a further design is not needed in this case, the material is enough to sustain the whole designing load.

3.4 DESIGN OF THE ELBOW MOTION

The total torque acting up to the elbow is calculated. Accordingly, the servotorque and gear ratio are calculated.

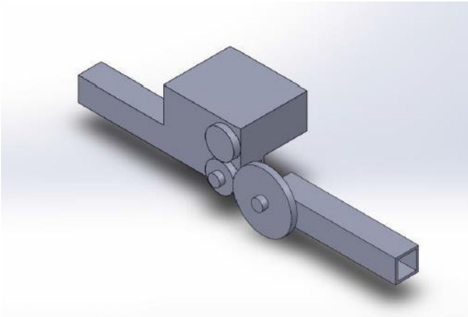

Fig-7: CAD model of the elbow motion.

The total torque acting and the gear ratio calculations are shown below. All the iterations are taken into account. Hence, an average value is taken.

$$\rightarrow Torque\ acting, T = (2.06 \times 55) + (2.4 \times 70) + (6 \times 110) + (2.4 \times 175) + (40 \times 21($$

$$= 97.613\ Kgf\ cm$$

$$\rightarrow Gear\ ratio = \frac{100}{55} = 2$$

The torque has been normalized with the first iteration results before finding the gear ratio. The servomotor selected here is 55 Kgf cm. This is deliberately selected to make the gear ratio as 2. Here, the degree of freedom is the up and down motion. The selected pinion diameter is 25 mm and the gear diameter is 50 mm.

3.5 DESIGN OF THE SHOULDER MOTIONS

There are two total arm movements to the current desi gn. The up and down movement, and the sideways movement. Since the torque acting is the same for both same gear ratio has been selected.

→ Torque acting, T= (5*70) +(7*140) +(2.06*220) +(2.4*235) +(6*275) +(2.4*340)

=198.13 Kg f cm

→ Gear ratio = 210/55 = 4

The selected pinion diameter is 25 mm and the gear diameter is 100 mm. The servo motor selected is 55 Kgf cm. For both the motion this servo motor is enough as it satisfies the torque parameter.

REASON FORTHE REJECTIONOF PNEUMATIC SYSTEM

The stroke of the piston used has been calculated from the pulley systems. There was a total ofthree pulleys (one above the elbow, one on the forearm, and the other on the upper arm). Initially, we assumed the distance to which the pulleys should be placed. Later, with that assumption, the angle to which the string is connected to the forearm is calculated. Then by reverse traverse, the whole values are calculated again. Hence, the correct distances and angles have been found. Based on the calculated results the air compressor specification is found out.

$$\rightarrow Diameter\ of\ the\ plastic\ pulley, d = 32\ mm$$

$$\rightarrow Motion\ of\ forearm\ from\ the\ ground = 70^{\circ}$$

$$\rightarrow Piston\ stroke, z = 60\ mm$$

Based on the above results the air compressor specification is calculated. The calculation is shown below.

$$\rightarrow Tension\ acting\ on\ the\ string, T = 344\ N$$

$$\rightarrow The\ angle\ to\ which\ the\ string\ is\ attached = 21.30^{\circ}$$

The pressure is calculated by using the torque and bore diameter (B). The parameters governing the motions could be found out from the below diagram. String is used for the connection betweenpulleys.

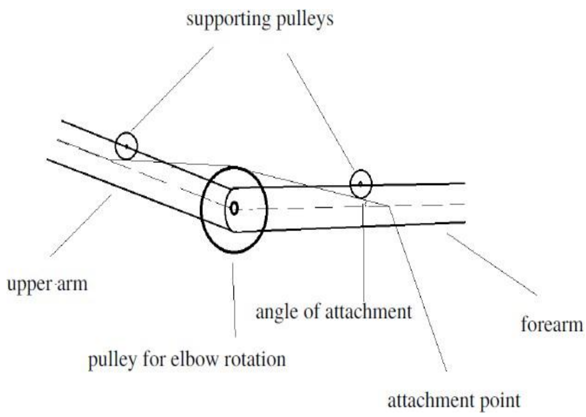

Fig -8: Diagram of the pulley system.

Pulley diameter is assumed as 32mm(based on the available dimensions in the market). The stroke of the piston we selected is 60 mm. Based on this the angle of attachment could be calculated. The degree to which the forearm make with the ground at the final position of the motion is 70 degrees.

$$Point\ of\ attachment\ of\ the\ string = \frac{Piston\ stroke}{\sin(70)}$$

$$Point\ of\ attachment\ of\ the\ string = \frac{60\ mm}{\sin(70)} = 64\ mm$$

Thus, the point of attachment of the string from the elbow to the forearm is 64 mm. Based on this parameter the angle of attachment can be calculated.

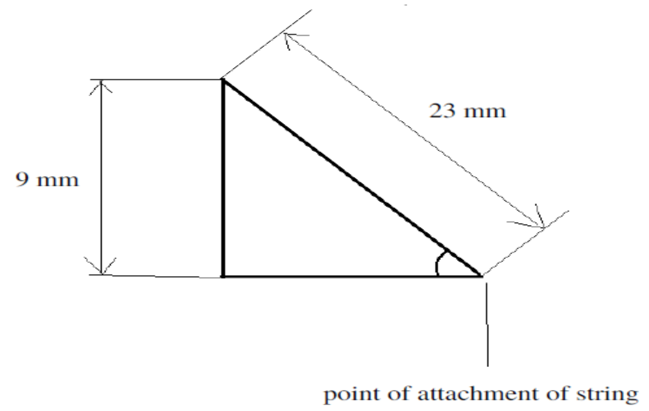

Fig-9: Triangle from the above figure.

Based on the point of attachment and the dimensions of the arm, the angle of attachment could be calculated. The effort acting there is 125 N. from this the tension acting on the string is calculated.

$$Angle\ of\ attachment\ of\ the\ string,\ \theta$$

$$\tan\theta = \frac{9}{23}$$

$$\rightarrow \theta = 21.37\,^{\circ}$$

$$Tension\ acting\ on\ the\ string = \frac{125}{\sin(21.37)}$$

$$Tension = 344\ N$$

$$\rightarrow pressure,\ P = \frac{F}{A}$$

$$\rightarrow P = \frac{4T}{\pi B^2}$$

$$P = \frac{4 \times 344}{\pi(30)^2}$$

$$P = 0.4866\ \frac{N}{mm^2} = 486660.44\ Pa$$

Pressure, P = 1.96 Mpa

Hence, the pressure that has to be generated here is 1.96 Mpa. This is the prime reason why we rejected the air compressor in the first iteration itself. The total weight of the compressor will be so large to generate such pressure. This requires additional support or facility tohold the compressor alone. This will affect the total design of the robot (the locomotion part). The design of the inserts will alsobe very complex if we intend touse the air compressor. Therefore, we set out to find an alternative for this system. The alternative we found out is the gear system. We notice that this system simplifies the total mechanisms. The final result comparison also validated our choice to not settle down with the compressor, piston, pulley system. The gear system came out to be a perfectchoice.

4. COMPONENTS

The components used are:

- 304 stainless steel wires
- AISI 4130 alloy steel rods
- Servo motors (elbow, shoulder, fingers and wrist)
- 304 stainless steel sheet metal
- AISI 4130 circular rods
- Bearings
- Revolute joint

5. ANALYSIS OF THE ARM

After finding the dimensions of the forearm and the upper arm rods, the entire arm has been analyzed. The arm is analyzed with the reference tothe pickupweight of 40 Nor 4 kg. The analysis is made in Ansyssoftware.

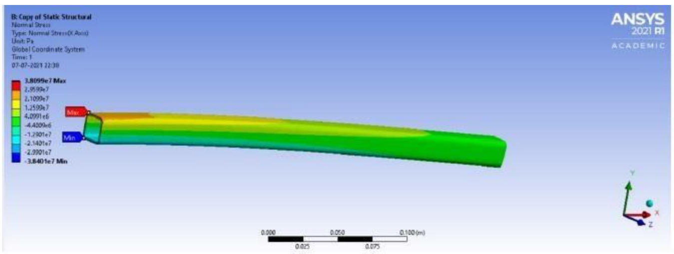

Fig-10: The results of the stress analysis.

The stress acting on the cantilever beam is 38 Mpa. The material used for the rods is AISI 4130. Thus, the factor of safety can be calculated.

$$Factor\ of\ Safety = \frac{Ultimate\ tensile\ strength\ of\ AISI4130}{Stress\ from\ analysis}$$

$$Factor\ of\ Safety = \frac{560}{38} = 14$$

Since the factor is 14, the arm can sustain the load under consideration. Then the analysis is made for the deflection.

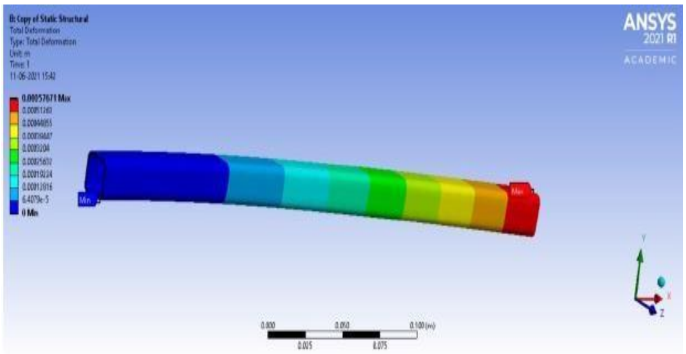

Fig-11: The results of the deflection analysis.

The deflection noticed is 0.05 mm. Hence, it can sustain a load greater than 40 N. The analysis made is by considering the beam as a cantilever beam. The additions to the beam are made later. The material used is AISI 4130, it is a highly strong material. This material can sustain the given load. The boundary condition used here is the fixed condition. The beam is a fixed beam. The maximumstress acts at the left side of the beam (denoted by the blue color). From both the analysis, it is evident that the beam can sustain the pick-up load and the design is successful (since the factor of safety is 14, it can handle way more load than this)

6. TOTAL DEGREES OF FREEDOM

A total of eleven degrees of freedom have been achieved for the arm from the current design. Taking inputs from the control systemteam the arm will execute all the degrees of freedom. All eleven degrees of freedomare listed below.

- The movement of five fingers - 5 degrees of freedom
- The rotational motion of the wrist - 1 degree of freedom
- The up and down motion of elbow part - 1 degree of freedom
- The up and down motion of the total arm - 1 degree of freedom
- The sideways motion of the total arm - 1 degree of freedom
- The movements in the X-Y plane - 2 degrees of freedom
- The movements in the X-Y plane are input from the locomotion team. This helped us to add two more degrees of freedom.

Fig -12: The concept of up and down rotation of the arm.

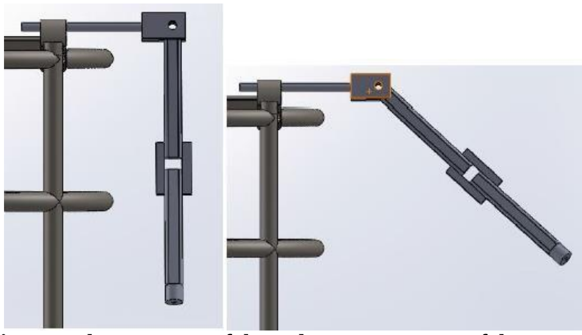

Fig-13: The concept of the sideways motion of the arm.

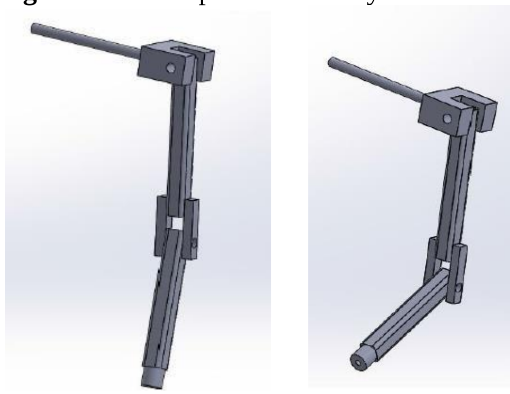

Fig-14: The concept of the up and down motion of the elbow

7. RESULTS

This animatronic arm has a number of important features. These features are very important for the overall functioning of the robot. The important features are listed below,

- Can pick a weight of atmost 4 Kg.
- Does not cause hindrance to the overall robot design and function.

- Has 11 degrees of freedom

The arm is designed by giving a constraint of 4 kg, that is 40 N. Since, the analysis results were satisfactory the arm The final degrees of freedom are so apt with the overall robot design. The up and down movements and the sideways movements of the arm will not affect the overall function of the robot. The current design of the arm has 11 degrees of freedom. This is depicted in detail in the previous papers.

8. CONCLUSION AND FUTURESCOPE

We begin the project to create an animatronic arm design that has essential degrees of freedom. We started the design by taking the measurements of an adult human arm. Since this is an adaptation of a human arm, we were allowed to make essential allowances within the design. With these measurements (length) we proceeded our project. Later we set out to find the dimensions of the steel rods (used as the arm), the strings, springs, sheet metals. We also found out the specifications of servo motors, gears used, bearings, revolute joints, connecting shafts. Some of the dimensions and specifications are taken as assumptions based on the whole geometry and design of the arm. We have done our initial analysis; the results gave a factor of safety of fourteen (14). This shows our design can sustain the load we anticipated. The materials used are of sufficient strengths, as even if some specifications are assumed the final design will sustain the anticipated load. Hence, we have successfully created the design of an animatronic hand.

Technology is advancing day by day; with this advancement it is possible to integrate more effective techniques in thefuture. The degrees of freedom can again be increased by carefully analyzing the human arm structure. With this assessment and integration, it is possible to make the design analogous to the human arm. The wrist motion can be made more realistic by providing motion analogous to the motion between radius and ulna.

Cost-effective materials should be traced out, there is future scope for this as the advanced technology will make the products much cheaper. If we can create a further efficient and cost-effective design, this would become much more useful. And, some small design changes will make this robot substitute for hazardous jobs.

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