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An Optimization Design and Analysis of Stair-Climbing Planetary Wheelchair

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***Abstract*—This paper designs a star-wheel stair-climbing mechanism. In this thesis, the design and analysis of an affordable automatic step climbing wheel-chair for the physically disabled are presented. The motivation is to cater to the needs of disabled people who are in an economically disadvantaged positions. A wheelchair is designed and analyzed with a planetary gear system attachment for the wheels. The structure and assembly of planetary wheels basic parameters required have been calculated for climbing steps without slipping. The stress analysis on the wheelchair has been performed for its various operating conditions. When the chair climbs stairs, there's a danger of falling down the steps, thence to guard the user to avoid this type of state of affairs to happen a ratchet mechanism lockup system is projected. The wheelchair assembly is modeled and its components are analyzed by considering three different materials under various likely possible loading conditions on a wheelchair with the help of finite element analysis software and the results are presented. Simulations in SolidWorksare made to verify the functionality of the proposed solution. The obtained results validate the proposed transmission model and enable the successful implementation of this design to a wheelchair experimental model.**

Keywords—Stair-climbing wheelchair, Star Wheel mechanism, SolidWorks modeling, Optimization design

I. INTRODUCTION

Day to day the number of patients with disabilities is increasing, nearly 15% of the world population are disabled according to “the globally disabled report”. Census 2001 has unconcealed that over twenty-one million individuals in India are full of one or the opposite quite incapacity, in movement (27.9%) is ascertained. A civilized society should guarantee honest living conditions for all its members, as well as disabled individuals. A civilized society must guarantee fair living conditions for all its people, including disabled people. Stair-climbing wheelchairs play an important role in the life of disabled people. Mobility is the most typical drawback for disabled folks, a drag that the introduction of power wheelchairs has done a lot to alleviate. However, a power wheelchair is useless when confronted with an architectural barrier. For this reason, several wheelchairs with stair climbing abilities have been developed. The invention of the wheelchair is one of the contributions for such physically challenged people. It is a boon for them. Since the day the chair was fabricated, it's been incessantly rising to boost its comfort level and with as several options as attainable. We’ve got to bump into many varieties of wheelchairs with completely different shapes, sizes, mechanisms, sources, materials, etc. We have carefully studied many types of wheelchairs with different shapes, sizes, mechanisms, sources, materials, etc. After the design of the planetary wheelchair, the proper selection of material is done, which shows that the wheelchair is very emphatic in terms of cost. Therefore, to solve the above problems and provide superior performance of the means of transport for the elderly and the disabled people, designing an inexpensive device for smooth and safe climbing stairs is of great significance and practical value. It not only has to resolve the inconvenience caused by the stairs in their lives but also considers users' affordability. In this project, we tend to design a replacement reasonably stair-climbing chair that encompasses a compact structure and will deal with flat or inclined pieces of land, stairs, and obstacles. All parts of the wheelchair were modeled in software Solid works, then simulation analysis to make sure the strength of the framework, gear shaft. Considering, the project design the Wheelchair height is 91cm and width is 76cm. We want that this work can become a contribution to society serving a sizable amount of disabled. Keeping all the on top of things in mind, focusing on the doable enhancements in wheelchairs, we got an idea of a stair-climbing wheelchair.

II. THEORY

A. Continuous Stair Climbing Wheelchair

The main property of the continuous stair-climbing wheelchair is that it only has one set of supporting devices; the wheelchair relies on this supporting device to realize continuous motions. According to the motion actuating mechanism, it can be divided into planetary wheel mechanism and tracked mechanism, and the tracked mechanism is more mature which is used much widely in stair-climbing wheelchairs.

Fig1 -Continuous stair-climbing wheelchair
Source:researchgate.in

B. Intermittent Stair Climbing Wheelchair

This type of wheelchair has two supporting devices, which alternatively work to complete the function of climbing. Intermittent stair-climbing wheelchairs are one of the oldest types of stair climbing wheelchairs. The operating of the mounting mechanism is: one in every of the support devices elevates the chair and also the alternative set of the network first; then a modification to the opposite set of supporting devices to support and take back the front of the support device, cycle as this till finished mounting all the steps. This type of wheelchair has low transmission efficiency and difficulty keeping balance.

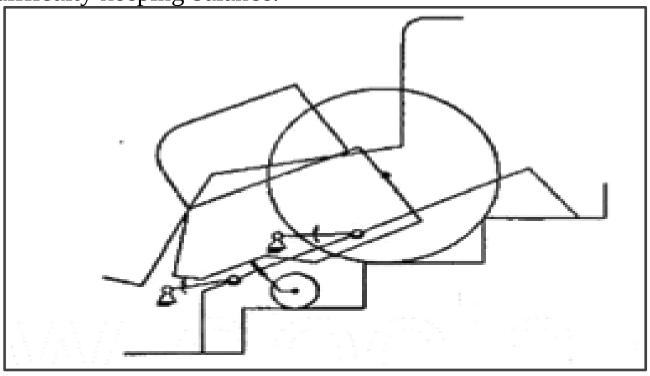

Fig2- Intermittent stair-climbing wheelchair
Source: researchgate. in

C. Auxiliary Stair Climbing Wheelchair

There is another stair-climbing wheelchair that relies on the other auxiliary device helping to achieve the function of climbing stairs, such as the stair-climbing wheelchair attachments and the stairlift in the below figures. The stair-climbing wheelchair attachments rely on another device installed on the wheelchair, and it needs an assistant to help to realize the function of climbing stairs; the stairlift requires wide stairways, and installation of the lift is very expensive.

Fig3 -Auxiliary stair-climbing wheelchair
Source:researchgate.in

III. METHODOLOGY

A. Walking Mechanism Design

The factors such as stability, safety, and comfort of the wheelchair directly come from the walking mechanism. According to our analysis, the following concepts were observed:

Planetary wheel mechanisms have a great advantage over other forms of stair climbing wheelchairs because they not only have simple and compact structures but also have flexible movement, good stability, and small fluctuation in the center of gravity. Therefore, we have selected a planetary wheel mechanism as our walking mechanism in our design.

The number of planetary wheels is often 2, 3, or over 3, to understand the necessities of tiny volume, lightweight weight, thought of the overturning moment, and wheel cluster center fluctuation, 3 planetary wheels were chosen, symmetrical arrangement, the structure is evolved from 2K-H epicyclic wheels system. And the two casters are installed which is used for turning and supporting the wheelchair

B. Theoretical Design and Calculation

First, the structure dimensions are determined to model the wheelchair and then for different motion modes stress analysis is carried out. Finally, the pulling force is estimated.

1. Determination of Basic Parameters of Planetary Wheel Systems

The structure of the wheel size is determined by the staircase. Also, during the process of climbing the stairs, the wheelchair requires stable support on the stairs. If the diameter of the wheels is simply too massive, the chair is unable to support itself on the steps, and it's additionally not smart for reducing the quantity of the wheelchair; if the diameter is simply too little, the chair can have an occasional potency once it moves on the flat ground, and it's a poor ability to adapt to the tract. The step-wide 'G' and also the step-height 'R' are determined by the step style rules. The dimension of the staircases ought to be less than 240mm; the height shouldn't be over 190mm. The design of the stair-climbing wheelchair

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should have stable support in the minimum width of 240mm, and can also roll at a certain distance. So here the width of the stairs b=240mm, and the height h=130mm are chosen. The radius of the wheel 'r' is 80cm. The following calculation is carried out, based on the geometry.

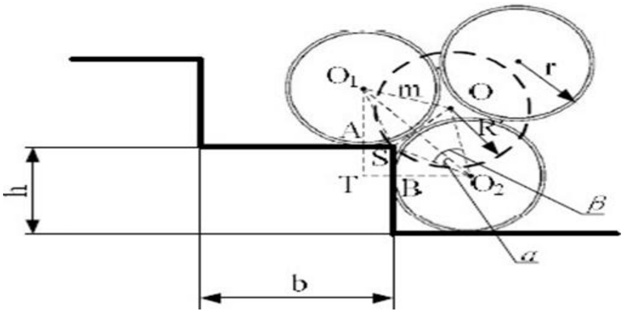

Fig4 [1]: Structure diagrams of the planetary wheels

$SO_2 = \sqrt{BO22 + BS2} = \sqrt{r2 + (h-r)2} = 94.33$

$O_1O_2 = 2m\cos 60° = \sqrt{3}$

$SO_1 = \sqrt{O1A2 + AS2} = \sqrt{(\sqrt{(3m2 - h2)} - r2)2 + r2} = 82.67$

Therefore,

$$\cos cos a = \frac{SO_2^2 + O_1O_2^2 - SO_1^2}{2SO_2 \times O_1O_2} = \frac{h(h-r) + r\sqrt{3m^2 - h^2}}{m\sqrt{3r^2 + 3(h-r)^2}} = 0.938$$

Considering the structure limits and non-interference between the planetary wheels, the rotation arm m=104mm is selected, based on the geometrical relationship r=80mm is calculated, then substituting the value of m, r, h into the equation, α=20.18° is calculated.

Therefore：

$$\beta = \alpha + 30° = 50.18°$$

$$R_{max} = OS = \sqrt{OO_2 + SO_2^2 - 2OO_2 \times SO_2 \cos\beta} = 80.29mm$$

The maximum dimensions of the driveshaft center should not exceed the radius Rmax, to ensure that there is no interference between the wheelchair and the edge of the stair when the wheelchair climbs the stairs.

2. *The condition of climbing stairs without slipping*

The distance between the front and back wheel should be 1m. Let the distance between the gravity center and back wheel be 'x'.

According to the force and moment equilibrium principle, the subsequent equations are obtained,

$$N_y = xG$$
$$N_1 = (1-x)G$$
$$N_x = N_y tg30°$$

To make the wheelchair climb upstairs without slipping has to meet the requirement of the following condition. $\mu N_1 \geq N_x$

$$\mu(1-x)G \geq x \times G \times tg30°$$

Friction coefficient = 0.3 is chosen here,

$$0.3(1-x)G \geq 0.58x$$

$$x \leq 0.34$$

For the wheelchair to be safe enough, the center of the gravity should be close to the rear part of the wheelchair. So, the location of the gravity center is set at x=0.25 m from the rear wheel, which can realize the condition of climbing stairs without slipping.

3. *Stress Analysis*

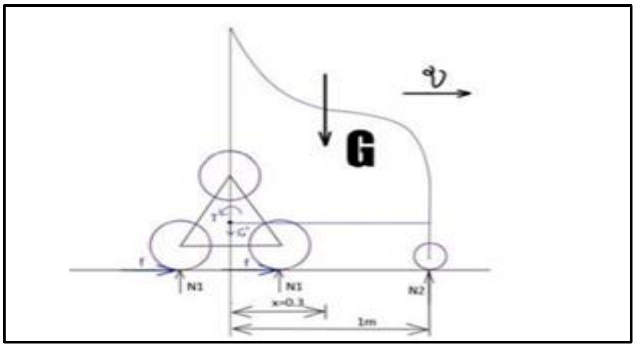

Fig5[1]-Moving on the ground level

When the speed of the wheelchair is constant, the following equations are obtained,

$$f_{Friction} = F_{Resistance}$$

$$T = f \times r$$

Where 'r' is the radius of the wheel, is the moving resistance which is very small and is to be neglected. Since the force exerted on the transmission gears is very small, the wheelchair is moving in a good stress condition.

4. *Stress analysis for the wheelchair moving on a sloping Ground*

The degree of slope is supposed to be 8 as the figure below; the positive pressure can be calculated by the following equation-

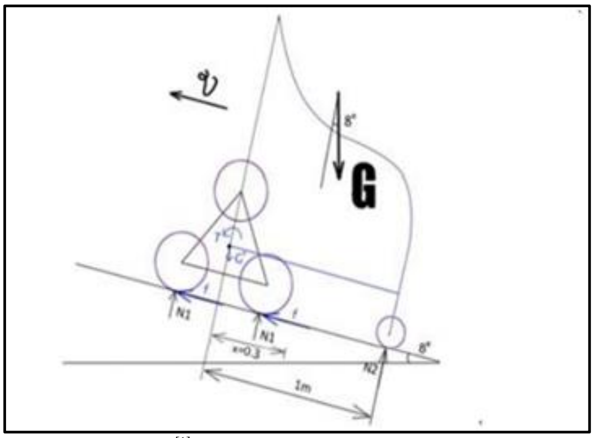

Fig6[1]-Moving on a sloping ground

$$f = \mu N_1$$

$$2N_1 = (1-x)G \times cos8° = 445.6206309\ N$$

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$$N_1 = 222.81\ N$$

$$f = \mu N_1 = 0.3 \times 259.95 = 66.84\ N$$

$$T = f \times r = 5.347\ Nm$$

5. *Stress analysis for climbing stairs*

The gravity can be transmitted to the planetary wheel system which is marked as G´, which plays two major roles when the wheelchair climbs stairs, one helps the planetary wheel turning, the other hinders the planetary wheel. The calculation obtained is as follows,

G' = 1 - xG = 0.7 × 600 =450 N

The balance equation for point A :

T = G'mcosθ = 42.75cosθ Nm

Where T is the torque, G´ is the total gravity of the wheelchair which is acting on the planetary system. The total weight of the wheelchair with the user is considered to be M=120kg. And the single side gravity G=60×10=600N, m is the length of the turning arm which is: m=104mm=0.104m

It is obvious that when the rotating arm of the planetary wheel in the horizontal state, i.e., θ=0, the distance between the bar center of the wheelchair and the supporting point of the planetary wheels train is farthest and where it also needs the maximum motor torque,

T_{max} = 42.75 Nm

The results which are calculated in the above three situations are listed in the table below

TABLE I

SITUATION	TORQUE
Moving on ground	T1 = 0 N. m
Moving on slope	T2 = 5.347 N .m
Climbing stairs	T3 = 42.75 N. m

Fig i. - Result of different move modes

6. *Pulling force estimation*

The distance from the fulcrum to the handle 'D'and the maximum torque 'T_{max}' were measured to be 0.91m and 42.75 Nm respectively, which we already calculated in the last section. According to the moment equilibrium theorem, the force which people use to pull the wheelchair up a stair can be calculated:

$$F_1 = 54.6 \div 1.173 = 46.97\ N$$

$$F_p = 46.55 \times 2 = 93.95\ N$$

This force is the maximum critical point force during the process of climbing up and down the stairs because the driving force will be provided by the motors which will be presented in the motor selection section. The main role of the assistance is to assist the wheelchair from falling back while climbing the stairs.

C. Transmission System Design

In this section firstly we will be dealing with the design and the principle of the transmission system and then the selection and assembly of gears in a planetary wheel. Also, the motor selection and battery selection as well be determined.

1. *Working principle for the transmission system*

This wheelchair was designed to be used in flat, inclined ground, obstacles. An epicyclic gearing was selected as the transmission system for each locomotion unit, where the two degrees of freedom are wheels and planet carrier rotations. For the wheelchair to have a specific motion, two inputs must be given to every locomotion unit. The working principle of the stair-climbing mechanism is: one input comes from two motors driving solar gears of the planetary wheels system, and the other degree of freedom is fixed by the ground. When the surface of the ground has low friction, the other input can make the real-time adaptive adjustment according to the road conditions i.e. When the wheelchair is climbing stairs, one of the degrees of freedom is constricted by the stairs and the wheel cluster can develop into a planetary wheel system, the planet carrier drives the other two wheels throughout the wheel in which degree of freedom is constrained to attain the function of climbing stairs.

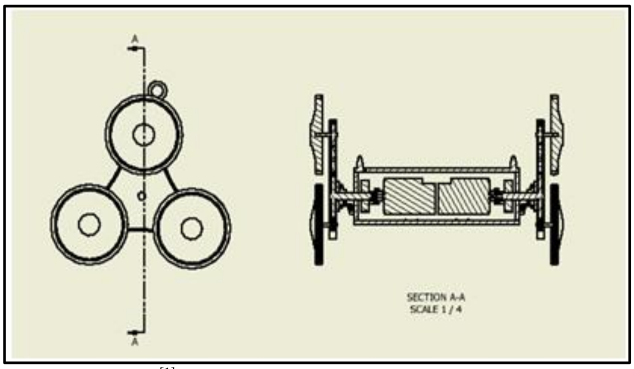

Fig7 [1]-Section views of the planetary wheels

2. *Gear selection*

In this section, the gears inside of the planetary wheels cluster, the teeth, and the modulus for each gear will be selected [1].

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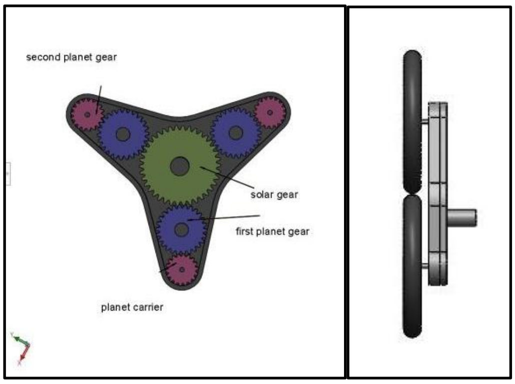

Fig8 - Structure of the planetary wheel cluster

In the above sections of this paper, we found out about stress analysis of three different motion modes and their comparison, the maximum torque at which the wheelchair can climb up and down, size requirements of the planetary wheel. To decrease the installation accuracy, the modulus of gears is selected as m=3 and the number of every gear tooth is supposed as z_1=38, z_2=26, z_3=18, and 45 steel quenched and tempered gears are chosen, the strength checking on the center gear z_1 as follows[1],

$$T_{max} = 42.75\ Nm = 42750\ N.mm$$

Where, $Y_N = 2,\ Y_{st} = 2,\ S_{film} = 1.5;\ \sigma_{Film} = 270MPa$

$$\sigma_{FP} = \frac{\sigma_{Film} + Y_{st}}{S_{film}} \times Y_N = \frac{270 \times 2}{1.5} = 720\ Mpa$$

$$\sigma_F = \frac{2KT_1}{\psi_d m^3 Z^2} \times Y_{Fa} Y_{Sa}$$

$$= \frac{2 \times 1.5 \times 54.6}{0.08 \times 3^3 \times 38^2} \times 2.8 \times 1.52 = 2.2351 < \sigma_{FP}$$

Where, $Y_{Fa} = 2.8,\ Y_{Sa} = 1.52,\ \psi_d = 0.08,\ K = 1.5$

From the above calculations, the gears can meet the requirements.

3. Motor Selection

1) Speed determination

The tooth of the sun gear is 38, the idle gear is 26, and the planetary gear is 18, the module is 3. Design standards of wheelchairs state that the moving speed of electric wheelchairs should not exceed Vmax = 2 m/s, and then transfer it to angular velocity as follows:

$$n = \frac{60 \times v}{2\pi \times r} = 238.73\ r/\ min$$

So, the angular velocity of central gear is

$$\frac{z_1}{z_3} = \frac{n_3}{n_1}$$

$$\frac{38}{18} = \frac{238.73}{n_1}$$

$$n_1 = 113.08\ r\ /\ min$$

2) Power Check

Since, the rolling friction coefficient between the tire and the normal road surface is 0.02, which was decided by checking the mechanical design manual, we should take safety factor Ks=1.5 and the total weight of a person and the wheelchair to be 120kg. The power required when the wheelchair works are, The motor is primarily used as the engine when the wheelchair moves on the ground or climbing up and downstairs, so the rated power should be much bigger than 90W. Based on this the type MY1016ZL 24V 250 W is selected, and the motor´s technical parameters are in the list in the table below.

$$P = K_s \times fmgv = 1.5 \times 0.02 \times 120 \times 10 \times 2 = 72W$$

TABLE II

Model	Working voltage	Starting current	Rated Torque	Noise
PM BLDC	24V	3A	45Nm	<60DB
	Output Power	Operating Speed	Reduction Ratio	
	below 1100W	75 rpm or 120 rpm	40:1	

4. Storage Battery Selection

There are various types of rechargeable batteries: lead-acid battery, nickel-cadmium battery, nickel-metal hydride battery, lithium-ion rechargeable battery, etc. We have chosen a lead-acid battery because of the following reasons:

1. Lead-acid batteries have the advantage of long service life, low price, and can store a large current discharge.
2. It has a small volume and is lightweight.
3. The selected motor needs a 24V storage battery.

And the parameters of the lead-acid battery is shown in the table below-

TABLE III

ITEM	Voltage	Capacitance	Outline Size	Weight
Lead Acid Battery	12V	1.2 Ah	98mm x 43mm x 52mm	0.5 Kg

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5. *Material Selection*

We have followed two principles in selecting the material. The two principles are: selecting the materials based on the strength theory and selecting the material based on stiffness theory.

The factors such as comfort and environment friendliness will also be considered.

From our design, the primary stress act on the frame is tension so principle one based on strength theory is applied to choose our material.

$$\sigma = \frac{F_N}{A} \leq [\sigma]$$

$$\sigma = \frac{F_N}{A} = \frac{93.1}{\pi \times 0.01^2} = 0.296MPa \leq [\sigma]$$

Where $F_N = F_P$, F_P is the pulling force

In the existing models, the manufacturers have chosen aluminum alloy or Titanium as the wheelchair materials. This difference between Mild steel and Alloy Steel will be presented in the analysis section. Also, this Alloy steel is used as it meets our strength requirements. The simulation and analysis will analyze which material has better properties.

IV. OPTIMIZATION DESIGN

To improve our wheelchair, the following optimizations are designed: planetary wheels mechanism optimization, locking system, and improvement on comfort and convenience.

1. *Locking Wheel System Design*

When the wheelchair is climbing, there is a chance of falling, to overcome this problem; we have installed a ratchet mechanism locking system on the central axis. This will help people lock the wheelchair and prevent falling.

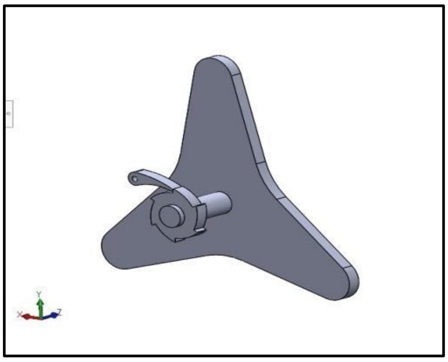

Fig9 - Locking Wheel System Design

2. *Ergonomics Design*

To make the wheelchair more convenient and comfortable for disabled and elderly people, we have optimized the structure of the stair-climbing wheelchairs based on the methods and principles of ergonomics.

i. *Folding Desk*

We have added a desk in our design to make the lives of the disabled and elderly more convenient.

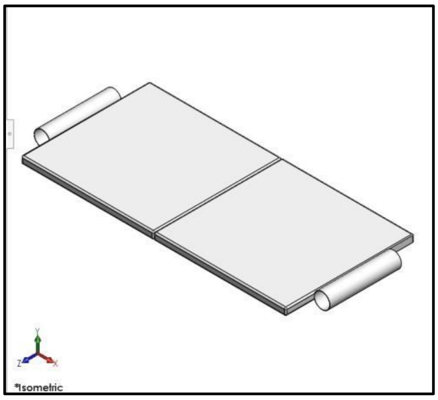

Fig10 – Folding desk

ii. *Shopping basket*

We have also added a shopping basket in our design to ease the load of carrying it in hands or on lap. We have fitted this shopping basket below the wheelchair and behind the leg space.

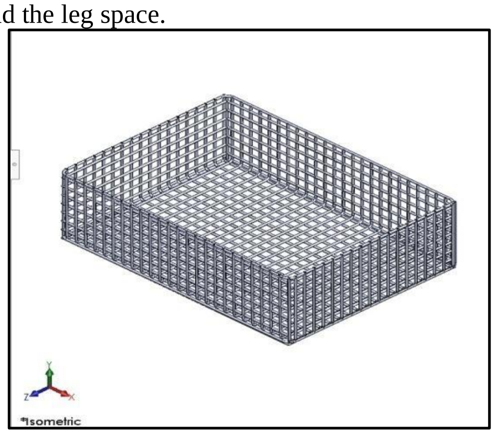

Fig11 – Shopping Basket

iii. *Curve design of the seat*

Since elderly and disabled people sit on our wheelchairs for a long time; this can cause pressure sores, so to overcome this problem we have made the shape of the seat to be curved which meets the requirements in design and comfort.

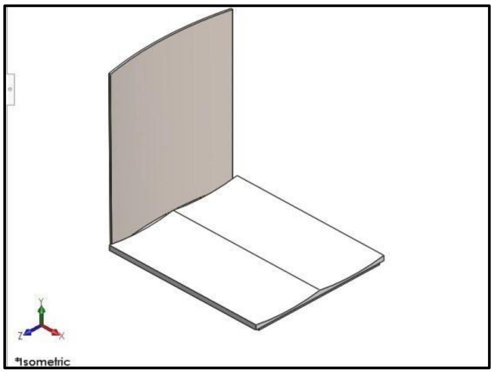

Fig 12– Curve design of the seat

V. MODEL

Solid works mechanical design automation software is a feature-based, parametric solid modeling design tool that takes advantage of the easy-to-learn Windows graphical user interface.

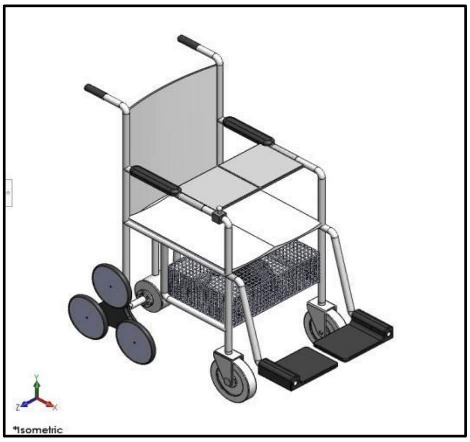

Fig 13– Solidworks Model

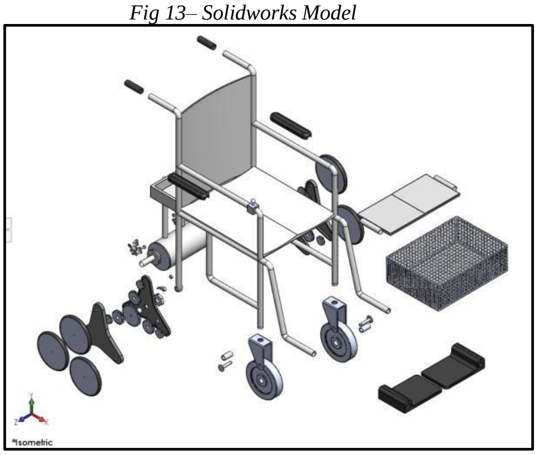

Fig14-Exploded View of Cad Model

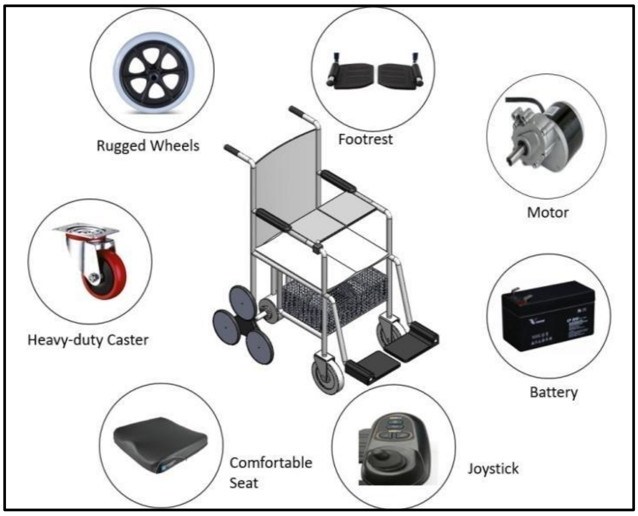

Fig15-Units of wheelchair

VI. SIMULATION AND ANALYSIS

Static Structural Analysis was done for the necessary parts which contribute to the major strength and can be considered as structural parts of the system. This uses Finite Element Analysis by creating proper meshing. We have evaluated Equivalent Von-mises stress, Displacement, Safety of Factor in the given parts.

The difference between Mild steel and Alloy steel material selection is shown in the body frame of the wheelchair.

A. Strength analysis of frame

1. Alloy steel

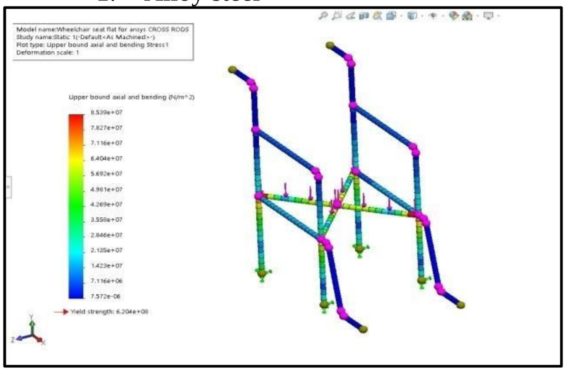

Fig 16 – Von mises stress of frame

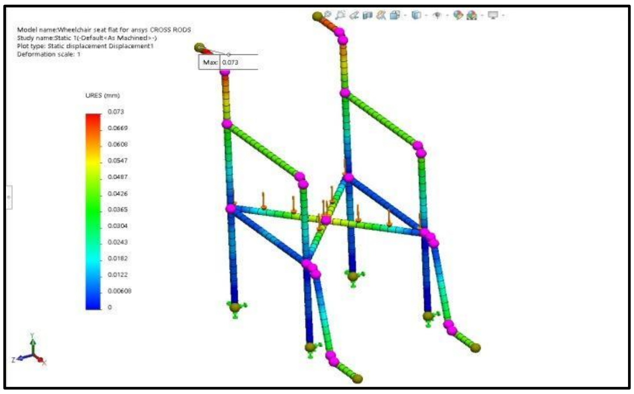

Fig 17-static Displacement of frame

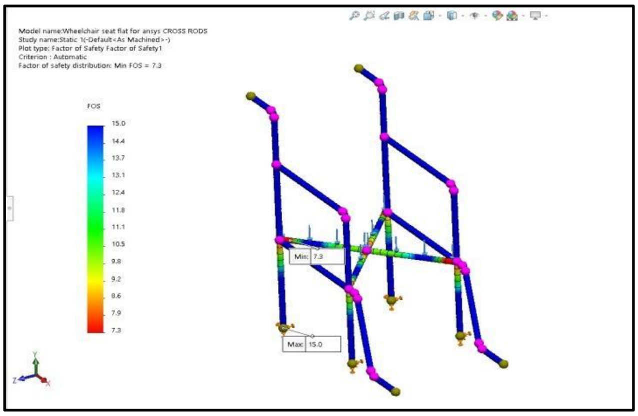

Fig 18- Factor of safety of the frame

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2. Mild Steel

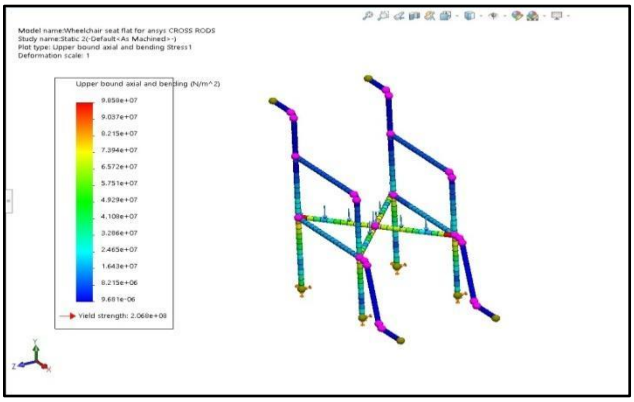

Fig 19 – Von mises stress of frame

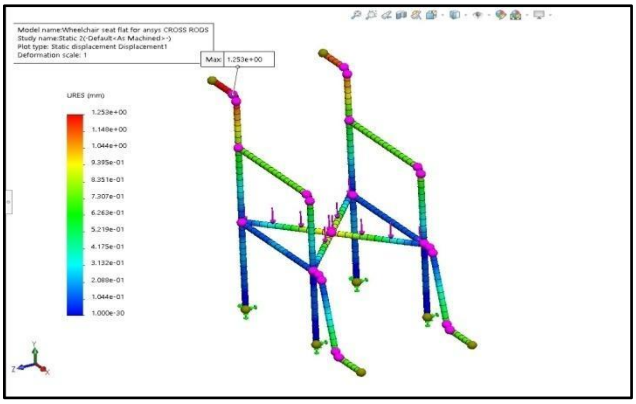

Fig 20-static Displacement of frame

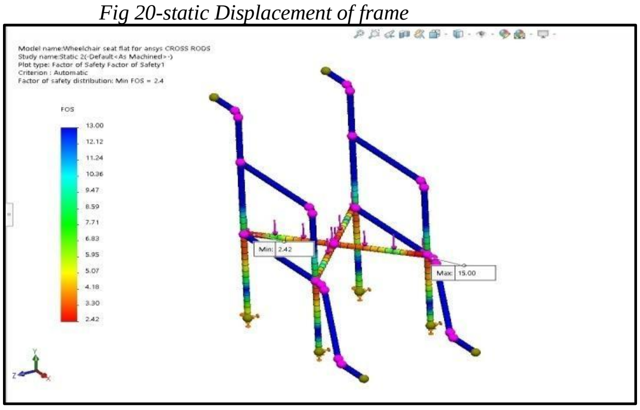

Fig 21- Factor of safety of the frame

B. *Strength analysis of Racket –Locking device*

Now we can make sure that the strength of the locking device is strong enough, to keep the wheelchair climbing up and down a stair without slipping down. We have estimated the maximum torque when a wheelchair goes upstairs, which is T_{max} = 42.5 Nm, so we check on this maximum torque if the locking device can work, and is strong enough. The figure of Von Mises Stress, Safety factor and Displacement is shown below:

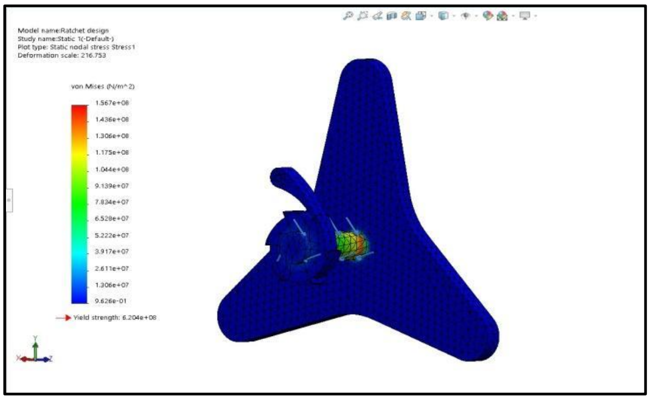

Fig22-Von Mises stress of the ratchet

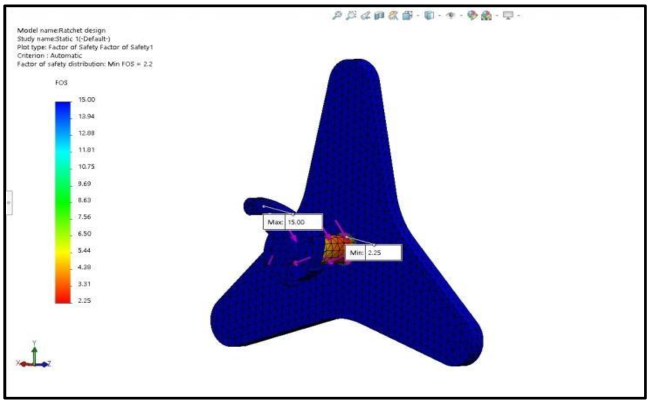

Fig23- Displacement of the ratchet

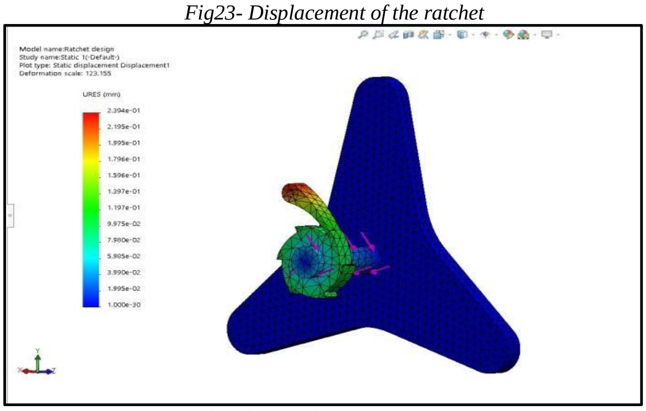

Fig24- Safety factor of the ratchet

VII. COST ESTIMATION

TABLE IV

Component	Material	Quantity	Cost(Rs)
Wheelchair Frame	Alloy Steel	1	3000
Planetary gear system	Gray cast iron	2	500
Motor	PM BLDC	2	12800
Battery	Lead Acid	2	1300
Caster Wheels	Cast Iron	2	450
Basket	Plastic	1	200

Desk	Plastic	2	200
Ratchet	Cast Iron	2	150
Foot-Rest	Aluminum	2	220
Wheel	Gray cast iron	6	1000
Electronic Control Unit	-	1	3500
Other	-	-	2500
Total			25820

VIII. RESULT

A. *Parameter comparison of Wheelchair frame*

TABLE V

	Max	Max	Max	Min	Min	Min
	Aluminium-6061[1]	Alloy Steel	Mild Steel	Aluminium-6061[1]	Alloy Steel	Mild Steel
Von mises stress	84.2	85.39	98.58	0	0	0
Displacement	0.098	0.073	1.253	0	0	0
Safe factor	15	15	13	8.1	7.3	2.42

B. *Parameter of Ratchet*

TABLE VI

	Maximum	Minimum
Von mises stress	150.5	0
Displacement	0.239	0
Safe Factor	15	2.25

IX. CONCLUSION

We have designed a new kind of stair-climbing wheelchair, which has a compact structure, which can be used on flat, inclined and stairs. All of the parts were modeled in SolidWorks and simulation was done to make sure the strength of the framework and desk. The results obtained are:

1. Design and modeling of the walking mechanism and transmission system, according to the standard calculations which decide the structure of the framework were done.
2. The addition of a basket based on the ergonomics design has made the wheelchair more convenient.
3. A locking system was added to avoid the slipping of the wheelchair while climbing.
4. Strength tests of the framework and locking system were done in Solid Works to make sure the wheelchair is safe and reliable.
5. Assembling was done in Solid Works to avoid interference between other parts.
6. Two different types of material have been chosen to analyze in solid works and one material was taken for parametric comparison [1].

X. FUTURE SCOPE

Few improvements could be done in the future to increase safety and reliability.

1. Make the whole system automated
2. Add a clutch system to extend the life of gears
3. Develop the intelligent control making it more automated
4. Make a prototype and perform experimental tests on it. Then find new parts which need to be modified and improved.
5. Go up and down stairs without assistance.
6. Sensor detection and alarm systems can be installed which are used to notify the user when the wheelchair comes across obstacles.

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