Design and Analysis of an Uneven Terrain Freight Transportation Mechanism

Mr. T. Tilak Sai*, Mr. M. S. S. Markandeya Swamy*, Mr. K. Praveen Srinivas*, Mr. Y. V. S. Harsha*, Mr. A Phanibhaskar, Mr. P Ramprasad**, Dr BSV Ramarao****

***UG students, **Faculty, Department of Mechanical Engineering College, Pragati Engineering College (A)**

ABSTRACT: Wheels are optimal only in highly selective sites or limited artificial environment that we purposefully design to allow wheeled locomotion. They exhibit poor performance in variable terrain and is subjected to large scale wear and tear. Using idea of Theo Jansen's kinetic sculptor this paper aims to create a legged mechanism which can be used as an alternate for tyres over rough terrains. It is an 8-bar mechanism that mimic nature and come up with smooth walking pattern even in rough terrain. The system minimizes the loss of energy during locomotion and allows the vehicle to maintain a constant velocity and height over variable terrain. It is a single degree freedom system and foot of the system traces an ovoid path. The system is expected to have a large social impact as it reduces the cost involved in transportation over uneven terrains and reduces physical load for workers. It finds application in various industries like mining, military purpose etc. In this work a 4-legged Theo Jansen walking mechanism was designed using Catia modelling and a structural analysis on the same was carried out. Also, a real time working model of this mechanism was fabricated.

Key words: Design, Analysis, Mechanism, CATIA, Fabrication

INTRODUCTION AND LITERATURE REVIEW

Humans are mainly using wheeled vehicles for on the ground transportation. But if we look around in the nature, there is no biological creature moving on wheels. To move on the ground, living creatures use legs or crawl. Wheels are optimal only in highly selective sites or limited artificial environment that we purposefully design to allow wheeled locomotion. They exhibit poor performance in variable terrain and is subjected to large scale wear and tear. Compared to wheel locomotion, walking has many advantages: lower energy consumption, no need for roads, better to cross over obstacles, the contact with ground is in a determined point, the ground is damaged less. Hence, the scientists are trying to design vehicles which are using legs or other locomotion ways that are inspired from nature. The purpose of this study is to contribute to the area of mechanism design and optimization of a single-degree-of-freedom leg mechanism. The leg mechanism is considered to be very energy efficient especially when walking on rough terrains. This paper describes the design and fabrication process of a 2n-legged passive walker based on the work of Theo Jansen; the primary focus of this paper is the design of a crank-based leg linkage. Walking machines possess several advantages over wheeled machines in areas of variable terrain. Consider a wheel moving a constant velocity V; every point on its perimeter is moving at a constant velocity V tangent to the curve of the wheel as shown in Figure 1.1. A comparable walking mechanism would be one which moves at a constant velocity V, and where the "foot" of the walker traces out a similar circular path with a constant velocity V at all points on the path (also shown in Figure 1.1). The most obvious advantage of the foot over the wheel is that the foot may step over inconsistencies in the terrain. Local maxima and minima may be completely avoided by simply stepping over them. This results in less loss of energy during locomotion and allows the vehicle to maintain a constant velocity and height over variable terrain.

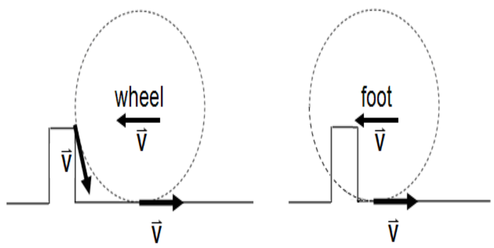

Fig 1.1. Comparison of wheel and foot response to a local maximum in the terrain.

The dotted lines indicate the perimeter of the wheel or the path of the foot. The arrows indicate the direction of movement. The foot may step over the obstacle completely, while the wheel must move over the obstacle. Now consider a case where the comparable foot and wheeled systems

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approach an obstacle that cannot be avoided, as shown in Figure 1.2. When the edge of the wheel makes contact with the higher ground, it forces the velocity of the vehicle to immediately slow. This edge has a total velocity V, but only a fraction of that velocity is in the x direction, so the vehicle quickly slows from V to Vx2. The foot encounters a similar change in velocity, but it has the advantage of being able to slide along the ground. Although this scenario is not ideal, dragging the front foot across the raised terrain reduces change of velocity in the x direction. Both models must still overcome the potential energy barrier posed by the increased height of the terrain.

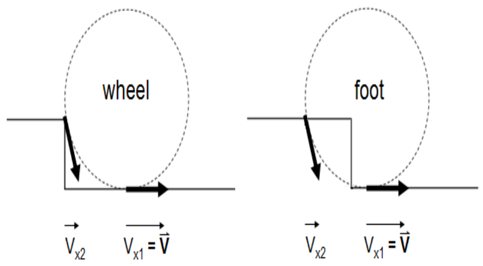

Fig 1.2. Comparison of wheel and a foot approaching an inconsistency in terrain.

A comparison of a wheel and a foot (moving in a wheel-like path) approaching an inconsistency in the terrain. The x component of the velocity of the edge of the wheel and the foot's path are indicated

Furthermore, the wheel causes a great deal of environmental harm. Its inability to avoid obstacles means that it erodes more terrain than a foot when moving comparable vehicles. Additionally, wheeled vehicles work best on terrain with no inconsistencies; this has led to paving of many permanent roadways, another form of environmental degradation.

The benefits of walking over rolling on rough terrain are summed up in the following:

- Higher energy efficiency, better fuel economy
- Increased speed
- Greater mobility
- Improved isolation from terrain inconsistencies
- Less environmental damage (both from paving and erosion).

Shansuk Nansai [1] (2013) analysed the dynamics of a four-legged Theo Jansen mechanism robot using projection method. The motion equation of the four-legged platform has been derived through individual modelling of forepaw and back paw and eventual integration of the two towards a complete system model. The unified dynamics expressions together with the numerical simulation, its analysis and results provide a solid foundation for the dynamics of the Theo Jansen mechanism. This research sets a theoretical basis for further investigation, optimization or extension of the Theo Jansen mechanism, in developing are configurable Theo Jansen mechanism and any potential application of the same for real world scenarios. Kazuma Komoda [2] (2014) demonstrated the lifting up of the locomotion pattern for climbing in bumpy conditions. The essence is to create a link between the rotation of the crankshaft and the up-and-down motion at the joint centre. The synchronous movement will help to create the new orbit of the leg's motion, and modify the original orbit to an orbit extending upward. Kazuma investigated the fundamental relationship between the crankshaft and the joint centre, a further step to propose a mechanism of the linkage between them to generate such a synchronous motion, for example a type of the crank rocker. This natural extension preserved the relationship between therefore limb and hind limb as anti-phase for moving forward. Amanda Ghassaei [3] (2015) described the design and fabrication process of a 2n-legged passive walker based on the work of Theo Jansen; the primary focus of this paper was on the design of a crank-based leg linkage. The linkage was simulated in Mathematica, and an analysis of the leg design, including an analysis of the foot path and centre of mass was provided and compared to the Theo Jansen mechanism. The results of the comparison found that the foot path of the new design is flatter and has a more constant velocity when it is in contact with the ground and the leg linkage requires 85% less vertical centre of mass movement during locomotion than the Theo Jansen mechanism, but its step height is about 33% less. M. Heinloo [4] (2015) presented the results of cinematic and dynamic calculations of Theo Jansen's walking linkage on the worksheet of Mathcad. The synthesis of a flywheel for Theo Jansen's linkage input link to decrease the fluctuation in its rotation is considered in detail. Danie Giesbrecht [5] (2014) A SDOF leg mechanism used by Theo Jansen was redesigned using mechanism design theory for the purposes of optimization. The mechanism design theory was found to be an excellent tool for determining the link lengths when incorporated into the optimization, because it offers a greater control on the outcome of each solution. The dynamic analysis was utilized in the optimization process to better simulate the forces in the joints and the torque on the crank. Overall, with the combination of the mechanism design and the dynamics, a very successful optimization was created where the energy and maximum crank torque were reduced drastically.

EXPERIMENTAL SETUP

This chapter explains in detail various components used in the fabrication of this paper. The important components used are a dc motor, spur gear mechanism, power transmission shaft, bearing with cup, cam mechanism, lead acid cell.

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3.1. DESCRIPTION OF DC MOTOR

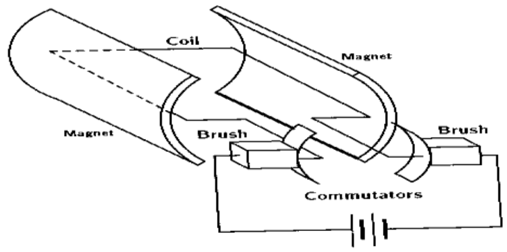

Fig 3.1 DC Motor

PRINCIPLES OF OPERATION

In any electric motor Fig 2.1, operation is based on simple electromagnetism. A current-carrying conductor generates a magnetic field; when this is then placed in an external magnetic field, it will experience a force proportional to the current in the conductor, and to the strength of the external magnetic field. As you are well aware of from playing with magnets as a kid, opposite (North and South) polarities attract, while like polarities (North and North, South and South) repel. The internal configuration of a DC motor is designed to harness the magnetic interaction between a current-carrying conductor and an external magnetic field to generate rotational motion. Let's start by looking at a simple 2-pole DC electric motor (here red represents a magnet or winding with a "North" polarization, while green represents a magnet or winding with a "South" polarization).

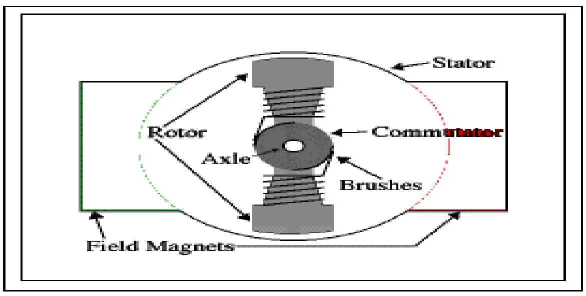

Fig 3.2 Sectional view of DC Motor

Every DC motor has six basic parts -- axle, rotor (armature), stator, commutator, field magnet(s), and brushes Fig 2.2. In most common DC motors, the external magnetic field is produced by high-strength permanent magnets. The stator is the stationary part of the motor, this includes the motor casing, as well as two or more permanent magnet pole pieces. The rotor (together with the axle and attached commutator) rotates with respect to the stator. The rotor consists of windings (generally on a core), the windings being electrically connected to the commutator. The above diagram shows a common motor layout -- with the rotor inside the stator (field) magnets. The geometry of the brushes, commutator contacts, and rotor windings are such that when power is applied, the polarities of the energized winding and the stator magnet(s) are misaligned, and the rotor will rotate until it is almost aligned with the stator's field magnets. As the rotor reaches alignment, the brushes move to the next commutator contacts, and energize the next winding. Given our example two-pole motor, the rotation reverses the direction of current through the rotor winding, leading to a "flip" of the rotor's magnetic field, driving it to continue rotating. In real life, though, DC motors will always have more than two poles (three is a very common number). In particular, this avoids "dead spots" in the commutator. You can imagine how with our example two-pole motor, if the rotor is exactly at the middle of its rotation (perfectly aligned with the field magnets), it will get "stuck" there. Meanwhile, with a two-pole motor, there is a moment where the commutator shorts out the power supply. This would be bad for the power supply, waste energy, and damage motor components as well Yet another disadvantage of such a simple motor is that it would exhibit a high amount of torque "ripple" (the amount of torque it could produce is cyclic with the position of the rotor). A few things from this namely, one pole is fully energized at a time (but two others are "partially" energized). As each brush transitions from one commutator contact to the next, one coil's field will rapidly collapse, as the next coil's field will rapidly charge up (this occurs within a few microsecond). We'll see more about the effects of this later, but in the meantime, you can see that this is a direct result of the coil windings' series wiring.

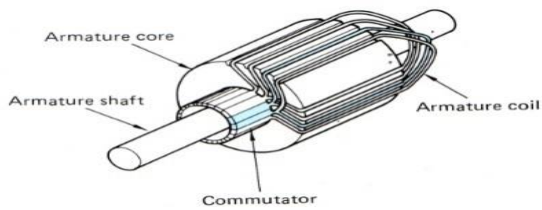

Fig 3.3 Armature of DC Motor

There's probably no better way to see how an average DC motor is put together, than by just opening one up. Unfortunately, this is tedious work, as well as requiring the destruction of a perfectly good motor. The use of an iron core armature Fig 2.3 is quite common, and has a number of advantages. First off, the iron core provides a strong, rigid support for the windings a particularly important consideration for high-torque motors. The core also conducts heat away from the rotor windings, allowing the motor to be driven harder than might otherwise be the case. Iron core construction is also relatively inexpensive compared with other construction types. But iron core construction also has several disadvantages. The iron armature has a relatively high inertia which limits motor acceleration. This construction also results in high winding inductances which limit brush and commutator life. In small motors, an alternative design is often used which features a 'coreless' armature winding. This design depends upon the coil wire itself for structural integrity. As a result, the armature is hollow, and the permanent magnet can be mounted inside the rotor coil. Coreless DC motors have

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much lower armature inductance than iron-core motors of comparable size, extending brush and commutator life.

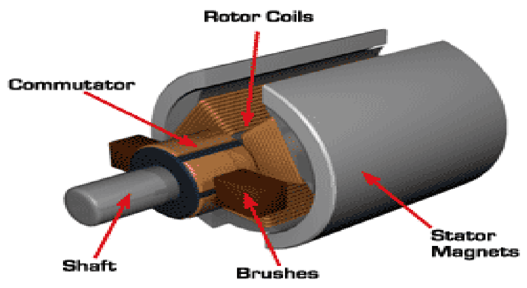

Fig 3.4 DC Motor Components

The coreless design also allows manufacturers to build smaller motors; meanwhile, due to the lack of iron in their rotors, coreless motors are somewhat prone to overheating. As a result, this design is generally used just in small, low-power motors. Beamers will most often see coreless DC motors in the form of pager motors. Again, disassembling a coreless motor can be instructive -- in this case, my hapless victim was a cheap pager vibrator motor. The guts of this disassembled motor are available Fig 2.4. This is (or more accurately, was) a 3-pole coreless DC motor.

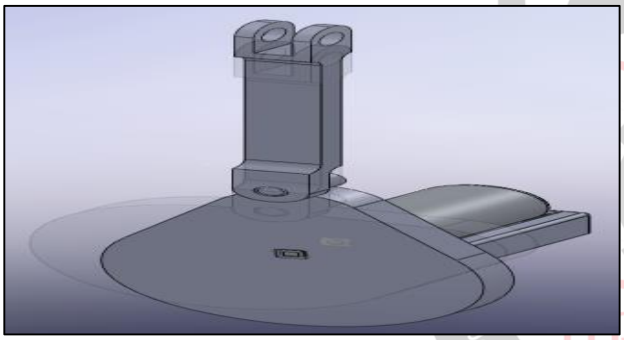

Fig 3.1 Cam mechanism

METHODOLOGY

This chapter explains the research idea, objectives of the work, a detailed description of the mechanism clearly indicating the movement of Theo Jansen mechanism. Details about designing of leg, Catia modelling of the 4-legged walker mechanism, its working, design of components and fabrication process also have been explained here.

PAPER IDEATION / BENEFITS OF PAPER

Wheels are optimal only in highly selective sites or limited artificial environment that we purposefully design to allow wheeled locomotion. They exhibit poor performance in variable terrain and are subjected to high wear and tear. Hence, we design a leg-based walking mechanism which can step over inconsistencies and exhibit good performance over variable terrain.

OBJECTIVES OF MODEL

To design, analyse and fabricate a leg mechanism for freight transportation over uneven terrains.

To carry out detailed study on the Theo Jansen mechanism and explore its various possibilities.

DESCRIPTION OF MECHANISM

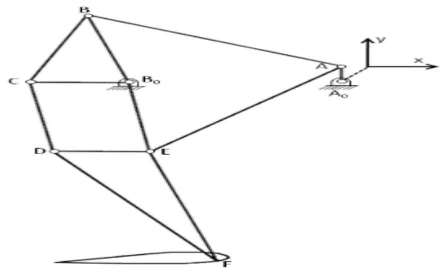

Fig.4.1 Theo Jansen Kinetic Sculpture

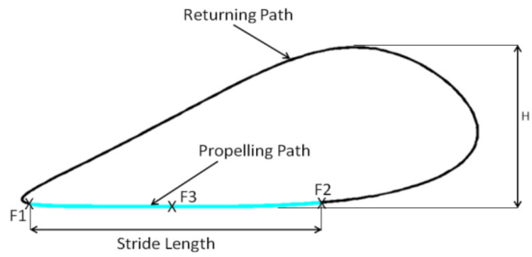

Fig.4.2 Walking path of the mechanism

The planar SDOF mechanism inspired by Mr. Theo Jansen's kinetic sculpture is an eight-bar mechanism shown in Figure 3.1, which consists of a pair of mirror-imaged four-bar mechanisms, A0ABB0 and A0AEB0, augmented with another four-bar linkage B0CDEF, where DEF forms one rigid link. The eight-bar linkage is equivalent to a six-bar mechanism from a design viewpoint since the four-bar linkages A0ABB0 and A0AEB0 are identical in dimensions. For convenience, an X-Y coordinate system is used for this mechanism with the x and y-axes pointing to the horizontal right and upwards where its origin is located at A0 as shown in Figure 3.1. To use this mechanism as a walking machine, link A0A serves as an input link and link.DEF serves as an output link with F as the tracer point, which is also called the foot point. The leg mechanism is designed to generate an ovoid walking path for two reasons:

(1) The ovoid path enables the walking mechanism to step over small obstacles without having significant elevation changes of the hip or without applying an additional DOF motion, and

(2) It can also minimize the slamming effect caused by the inertia forces during walking. The foot-point path is composed of two portions (Figure 3.2). First is the propelling portion, which is the flat portion of the path located between points F1 and F2. During this portion of the path, the foot-point F is in contact with the ground. The second is the returning portion, where the foot-point F is not in contact with the ground. The length of portion F1 to

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F2 is the stride length, and the height H is the maximum height of an obstacle that the walking machine can step over. Since the trajectory of the foot-point relative to the hip (A0B0) is a closed curve and A0B0 is10located outside the curve, a crank-rocker mechanism must be designed as discussed. Thus, in this work, A0A is designed as a crank. Lifting of the leg is achieved by a parallel linkage in the mechanism which is folded during cycle angling the lower portion of the leg.

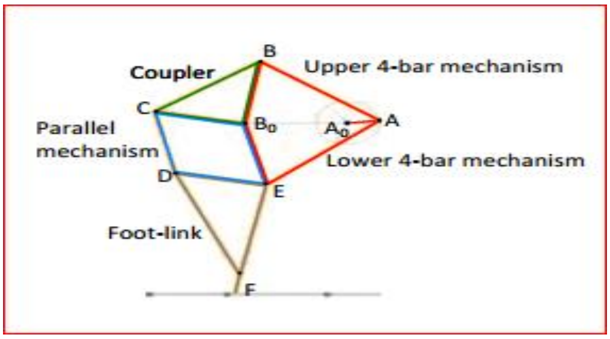

Fig.4.3 Linkages in the mechanism

DESIGN OF COMPONENTS

Selection of motor

Total load of the system =20 kg

Required linear velocity =0.1 m/S

Total power required, P =F. v

= (20*9.81) *0.1

=**19.62W**

19.62 = (T* **ω**)

Total torque required, T = (19.62*60)/ (2* π *10)

=**18.73N-m**

Power of motor selected =30W

Speed of motor =60rpm

ω =(2*60* π)/60

=**6.28rad/sec**

Torque of motor, T =P/ **ω**

=30/6.28

=**4.77N-m**

In order to increase the torque, a gear has been coupled with motor, with gear ratio of 1:6.

Therefore, torque output of the motor=**28.62N-m**

Output speed= 60*(1/6) =**10rpm**

Design of shaft

Diameter of shaft, D $= [16*M_t / \tau * \pi]^{1/3}$

$= [(16*18.73)/55*10^{-6}*\pi]^{1/3}$

τ =55MPa

D =0.01201m

= **12mm**

Selecting standard value by incrementing by steps of 5

Selected shaft is of diameter **15mm**.

Selection of bearing

Speed, N =10rpm

Radial load, F_r =170.27N

Axial load, F_a =61.97N

For shaft diameter 15mm, select a deep groove ball bearing of SKF 6203.

Static load capacity, C_o =4750NDynamic load capacity, C =9560N

Step:1

F_a/C_o =61.97/4750

=**0.013**

Select e=0.22

Step:2

F_a/F_r =61.97/170.27

=**0.363**

F_a/F_r>e

Select X=0.56, Y=2

Step:3

Equivalent load, P = $(XF_r+YF_a) *k_s$

Assuming k_s=1 (steady load)

P = (0.56*170.27) +(2*61.97)

=**219.291N**

Step:4

Life of bearing $=(c/p)^3$

$= (9560/219.291)^3$

=**0.082x10⁶ revolutions**

Required/Expected life=20 min/day for one year

= (20*365) *10

=**0.07x10⁶ revolution**

Therefore, bearing selected is safe.

The bearing used is SKF 6203.It is a deep groove type bearing.

Design of gear

Cast steel spur gear pinion having 9 teeth and rotating at 60 rpm is required to transmit 30 W to a high-grade Cast steel gear to run at 10 rpm

Speed ratio, i = n1/n2

60/10 = 6

No: of teeth on gear, z2 = i * z1

=6*9 =54

Allowable static stress,

Cast steel, σ_{01} = 135 MPa

Using Lewis form factor, y= 0.124-(.684/z), capacity (σ * y) was found to be less for pinion.

Hence design is based on pinion

Tangential tooth load, $F_t = \{9.55*10^6 PC_s\}/(n*r)$

Where,

P=Power in kw

C_S=Service factor

N=Speed of pinion in rpm

r=Radius of gear

$= \{9.55*10^6 *.030*1\}/(60*9)$

=530.55N

Dynamic tooth load, $F_d=F_t+\{21v(F_t+bc)\}/\{21v+(F_t+bc)\}$

b=Face width

c=Dynamic load factor

v=Velocity in rpm

=709.70N

Wear resistance, $F_w=d_1bQk$

Q=Ratio factor

K=Velocity factor

d=Diameter of pinion

b=Face width

=18*20*2*(54/54+9) k

=617.14k

For safe design,

$F_w>F_d$

617.14k > 709.70

k>1.149

Recommended hardness for gear=300BHN

4.6.5 DESIGN OF LEG

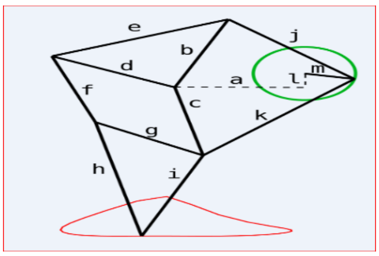

Fig.4.9 Nomenclature of links

Table 3.1 dimensions of link

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LINK	LENGTH (cm)
A	19
B	20.7
C	19.6
D	20
E	27.9
F	19.7
G	18.3
H	32.8
I	24.5
J	25
K	30.95

CATIA MODELLING

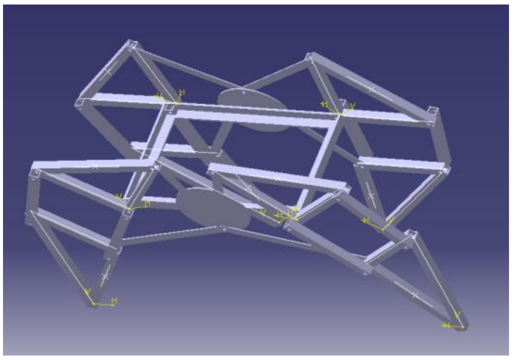

Fig.4.9: Top View

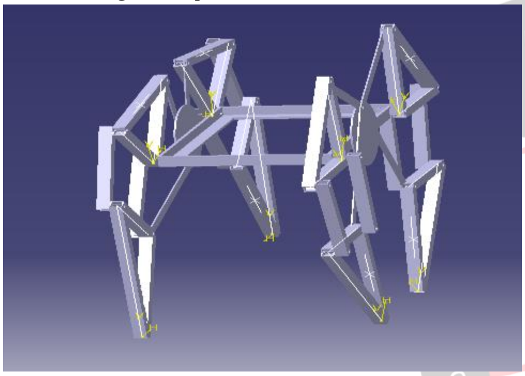

Fig.4.10: Front View

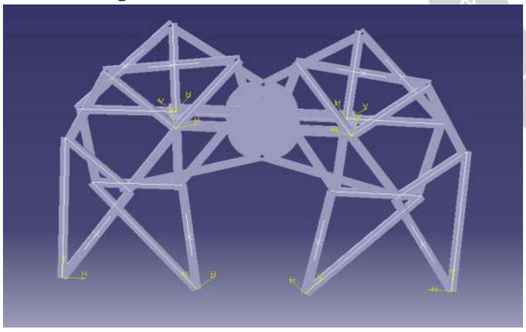

Fig.4.11: Side View

4.7 CENTER OF MASS

By assuming that the components of the linkage have a constant density, it is a straightforward exercise to determine the centre of mass throughout the locomotive cycle. If we assume that the mass of each rigid body in the linkage is equal to its length times a constant, then the centre of mass of each link will always be located at its centre. That is:

If: Mass = (constant) * Length

Then: x coordinate of centre of mass = $\frac{1}{2}(x_1+x_2)$

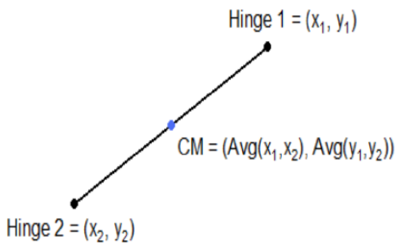

Figure 4.13: Determination of the position of the centre of mass of a rigid body of uniform density. The centre of mass is indicated by a blue dot and is located halfway between hinge one and hinge two.

Table.4.2. centre of mass

LENGTH OF LINK	DISTANCE FROM X-AXIS	DISTANCE FROM Y-AXIS
L1	X1=19.2	Y1=4
L2	X2=7.2	Y2=7.2
L3	X3=.8	Y3=14.8
L4	X4=-6.8	Y4=6.8
L5	X5=-14.8	Y5=3.6
L6	X6=-18.4	Y6=-22
L7	X7=-12	Y7=-28.8
L8	X8=-2	Y8=-9.2
L9	X9=10	Y9=-13.2
L10	X10=-10.4	Y10=-12.4

$\bar{x}$	$\bar{y}$
10.7	-5.75

RESULTS AND DISCUSSION

This chapter deals with the structural analysis performed on the above mentioned Catia model of the mechanism and experimental investigation of the step height and stride length of the same. The advantage, disadvantage and application of the work has also been mentioned

5.1 ANSYS ANALYSIS

Ansys Autodyne

ANSYS Autodyne is computer simulation tool for simulating the response of materials to short duration severe loadings from impact, high pressure or explosions.

Ansys Mechanical

ANSYS Mechanical is a finite tool for structural analysis, including linear, nonlinear and dynamic studies. This computer simulation product provides finite elements to model behaviour, and supports material models and equation solvers for a wide range of mechanical design problems. ANSYS Mechanical also includes thermal analysis and coupled-physics capabilities involving acoustics, piezoelectric, thermal–structural and thermo-electric analysis.

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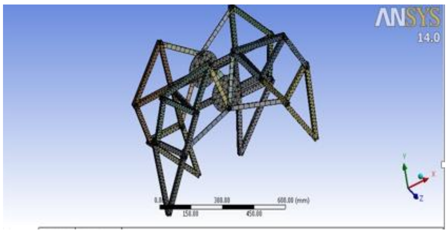

Fig 5.1. Meshing of Structure

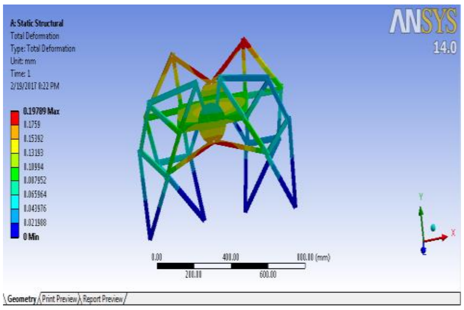

Fig 5.2. Total deformation analysis

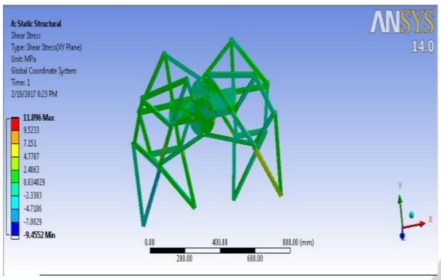

Fig 5.3 Shear stress analysis

5.2. LOCUS OF MECHANISM

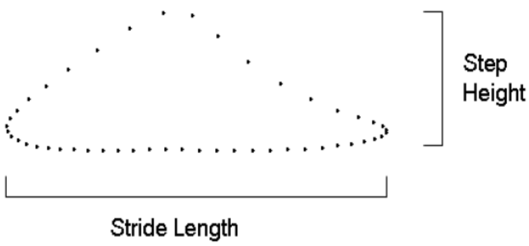

Fig:5.4 Locus of mechanism

Table5.1 Analysis of Theo Jansen locus

Stride Length	15.2 cm
Step Height	7 cm

CONCLUSION

This work has provided us an excellent opportunity and experience, to use our limited knowledge. We gained a lot of practical knowledge regarding, planning while doing this work. We feel that the work is a good solution to bridge the gates between the institution and the industries.

We are proud that we have completed the work with the limited time successfully. The "DESIGN AND ANALYSIS OF AN UNEVEN TERRAIN FREIGHT TRANSPORTATION MECHANISM" is working with satisfactory conditions. We were able to understand the difficulties in maintaining the tolerances and also the quality during the operation. We have done to our ability and skill making maximum use of available facilities.

In conclusion remarks of our work, let us add a few more lines about our impression work. Thus, we have developed "AN UNEVEN TERRAIN FREIGHT TRANSPORTATION MECHANISM" which helps to climb up the walls of high-rise buildings, uneven terrain at a significant low cost which may be used for several applications. By using more techniques, they can be modified and developed according to the applications.

The purpose of this study was to contribute to the area of mechanism design and a single-degree-of-freedom leg mechanism. The leg mechanism is considered to be very energy efficient especially when walking on rough terrains. Furthermore, the mechanism requires very simple controls since a single actuator is required to drive the leg. Our Paper describes the design and construction process of a 4-legged walking machine suitable for locomotion in variable terrain.

A simple, energy efficient leg mechanism inspired from Dutch kinetic sculptor Theo Jansen's "STRANDBEAST" for the movement over variable terrain was designed and fabricated.

The design of the 4-legged walker mechanism was made using modelling software CATIA and a structural analysis of the same was done in ANSYS to determine total deformation, shear stress, and strain on various elements of the mechanism.

Based on the work done and the further discussions, the conclusions are –

1. Energy efficient design.
2. Modelling of 4-legged walker was done using Catia software.
3. Structural analysis was performed using Ansys 14 to determine the shear stress, total deformation and shear strain.
4. The amount of energy used per locomotive cycle was minimised. This was accomplished by designing a linkage which minimizes torque on the crank and sequencing a gait in which the upward movement of one leg was cancelled out by the downward movement of another leg; this necessitated that the walker have 2n legs. Additionally, these legs were attached to a central crank axis so that they could be coupled. The legs will all be directly coupled to the same crank axis.
5. The linkage also allowed the main body of the vehicle to remain at a constant height throughout locomotion, which will minimize energy losses due to changing potential energy.

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6. Ability to avoid obstacles by stepping over them.

7. Statically stable during entire locomotive cycle.

For the mechanism to come to a stop at any point in the locomotive cycle, the vertical projection of its centre of mass must always be inside its base of support.

8. Durable joints/hinges/moving parts which will not become blocked by debris over time were used.

Since this walker will be moving across uneven terrain, it will most likely encounter obstacles that it cannot avoid. The linkage must be able to handle the stresses of irregularities in the terrain. The vehicle will be walking outdoors so the linkage should not include cam grooves or other parts that may become blocked by debris.

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