Toronto Metropolitan University

AER403 Mechanism and Vibrations

Walking Robot Design

Final Report

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Executive Summary

The objective of this project was for the team to design a walking robot mechanism using individual parts of a gearbox and a motor that was provided. The sole constraint that was placed upon the team was that any non-legged components may not be used. This included wheels, rollers, or continuous tracks.

The team conceptualized three different designs. The frog mechanism, the Theo Jansen mechanism, and the two-legged design mechanism. Each mechanism was animated and simulated in MATLAB and then designed in CATIA. For each design, extensive calculations were done to find the optimal gear ratio for the perfect balance between power and speed. A metric table was also made to compare the mechanisms to each other with regards to mass, cost, speed (theoretical), and manufacturability. [1]

After careful consideration and deliberation, the team unanimously agreed that the frog mechanism was the best choice, as it excelled in all metrics compared to the Theo Jansen mechanism and the Two-Leg design mechanism. Plans for manufacturing, detailed in the design methodology section of the report, were made but then unfortunately had to be discarded due the deadly pandemic that has been spreading through the world.

Introduction

This report will provide an overview of the mechanism that the team built. It includes a deep insight into the design selection process with analyses of three different designs that were brainstormed, the final design analysis and design methodology, and all MATLAB codes and/or CATIA models used during the design process.

Our team was given the task of building a walking robot using only a motor or an actuator. Only the motor and the gearbox (individual parts that had to be manually constructed and analyzed) were supplied and the mechanism surrounding the gearbox was also to be constructed by the team. The sole constraint of the project was that the robot may not use wheels or any other components that are non-legged, in order to complete its task. The three designs of our choice were to be surveyed and the basic type of each design was to be identified. We were also required to conduct displacement and velocity analysis of our mechanism and then create an animation in MATLAB.

It was a unanimous decision that the frog mechanism would be chosen. It excelled with regards to the other designs in terms of cost, mass, speed, and manufacturability. The Theo-Jansen design was deemed very costly and difficult to manufacture as very specific equipment would have to be used. The two-leg design mechanism was similarly discarded due to its lack of forward speed potential and issues with stability.

Design Selection

Design Objectives

1. Mechanical Constraints
   1.1. Powered by two AA battery cells
      1.1.1. 1.5V each
   1.2. Motion by gearbox crank axle
   1.3. No non-legged components
   1.4. Entire mechanism should be able to move forward as one
      1.4.1. Mechanism must be able to carry all the weight
2. Performance
   2.1. Minimum friction
   2.2. Maximum speed
      2.2.1. Most optimal gear ratio
3. Manufacturability
   3.1. Safe to operate
   3.2. Low cost
   3.3. Durable

Functional Analysis

The mechanism's primary function is to "walk" forward. To do this, input from the crank axle is needed and will provide an output would result in the walking motion of the legs of the robot. To accomplish this, torque would need to be generated from the gearbox which, in turn, needs an electrical current to move the motor. Metric system established to evaluate solutions:

Table 1 – Metric by points for design.

Metric	Points
Cost	3 – Very expensive 2 – Affordable 1 – Very cheap 0 – No cost.
Mass	3 – Very Heavy 2 – Moderately heavy 1 – Very light 0 – No Mass
Ease of Manufacturability	3 – Needs specialized manufacturing equipment 2 – Uses standard parts 1 – Can be made using homemade parts 0 – Very easy to manufacture
Speed of Movement (Theoretical)	3 – Barely moves 2 – Average speed 1 – Fairly fast 0 – Very fast

Design Concepts

Design 1: Frog Mechanism

The frog mechanism is a 4-bar linkage that contains two ternary links for the frame and the output link. A ternary link is a link that attaches to three joints in such a manner that it is considered as a single link. The ternary links in the frog mechanism are the red and green coloured links that are in the shaped of a fixed triangle, as seen in figure 1. By applying the following equation, the degree of freedom of the mechanism could be found:

$$DOF = 3(n - 1) - 2 \times f_1 - f_2 \qquad (1)$$

Where *F* is the degree of freedom (DOF), *n* is the amount of links, f_1 is the amount of 1 DOF joints, and f_2 is the amount of 2 DOF joints. The frog mechanism has only one degree of freedom which by inspection could be seen as rotation. Also, the ternary links of the frame and output provide a stable and strong support for the gearbox. The base of each ternary link is 5 mm wide allowing the weight of the gearbox to be uniformly distributed causing no high stress build-up/points on the contacting surfaces (contact with ground). Due to the gearbox's dimensions (72 mm × 24 mm × 34 mm) the frog mechanism had to follow some design constraints:

- The height of the frog mechanism had to exceed a height of 34 mm in order to displace the gearbox.
- The input link and coupler link had to be designed to allow ample spacing for the links to pass through during rotation of the mechanism without any collision.
- The output ternary link needed to be manufactured to allow for multiple high impacts without any damage or breaking by increasing the thickness.
- The frog mechanism had to allow the gearbox to be displaced large distances in a relatively short time frame.

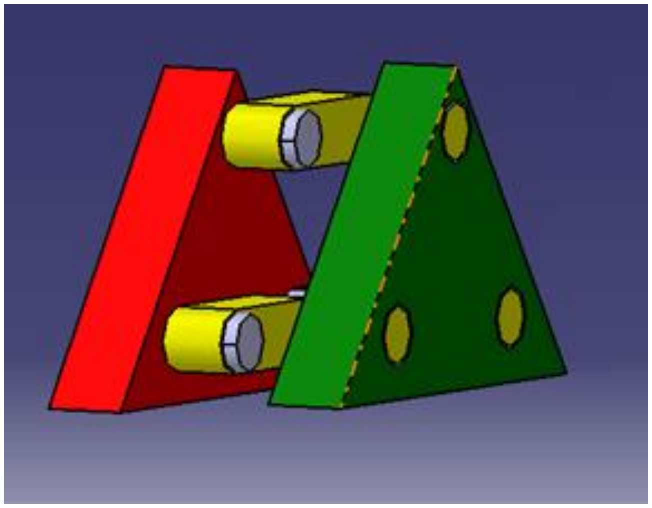


Figure 1 – Frog Mechanism

In figure 1, the red colour triangle shows the ternary link of the frame, the white coloured shaft represents the input shaft that will come from the gearbox, the 3 yellow links are the coupler links that allow the output to move given the input, and the green coloured triangle is the output ternary link.

The gear ratio of the robot design used for the frog mechanism is 126:1 (refer to figure 2), this will produce the maximum angular velocity of 105 RPM, which in turn causes the maximum velocity for the input link due to the relationship $V = \omega \times r$. All other configurations of the robot's gears will result in an angular velocity smaller than 105 RPM. Due to the task of the gearbox and mechanism the design team want to have a secure and fast operating mechanism that could displace the greatest distance the fastest.

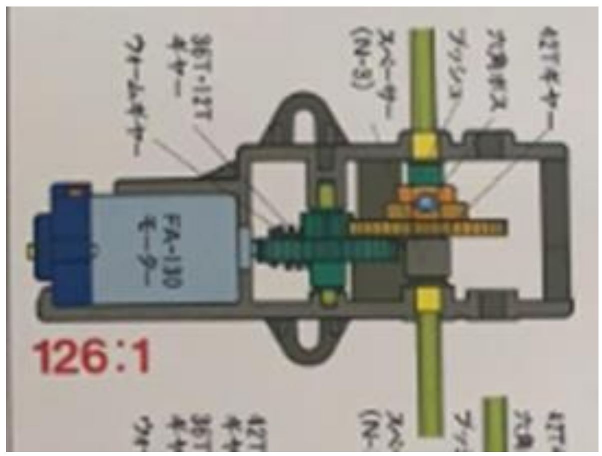


Figure 2 – Minimum Gear Ratio

The frog mechanism would be manufactured using ABS plastic to allow for high durability, low costs, light weight, and maximum efficiency. ABS plastic is commonly used in mechanical applications. The tensile strength of ABS is 46 MPa, which is high compared to other types of plastic filaments. The tensile strength is a measure of the maximum pressure needed to be applied to the substance before it breaks. By creating the frog mechanism with ABS plastic and 5mm thickness for the ternary links, the mechanism will be able to resistance high impact forces. The specific gravity of ABS plastic is 1.06, which is light weight. The lightweight material will allow the mechanism to operate with high efficiency and maximum output torque. ABS plastic is inexpensive to purchase and can be found easily on the market [1]. All these properties made ABS plastic the material of choice to manufacture the frog mechanism.

Design 2: Theo Jansen Mechanism

The Theo Jansen mechanism is a one degree of freedom mechanism composed of eight or more legs. The figure below illustrates a non-scaled diagram of one leg of the Theo Jansen mechanism which has one input(crank) link (m), two rockers link (b and c), and two couplers (j and k) which are all connected by pivot joints. This linkage is very similar to a Klan linkage.

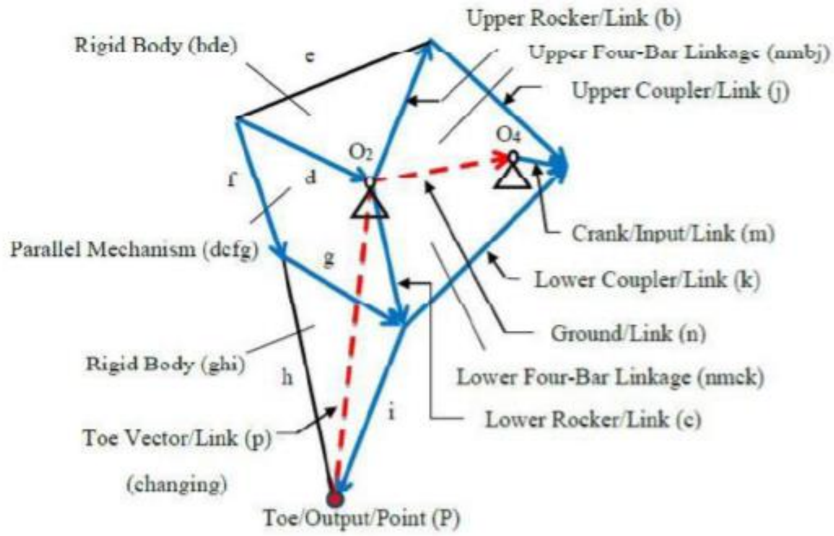


Figure 3 – Links and Linkages of Theo Jansen Mechanism.

Each leg consists of six parts as seen in the figure above:

1. Two three-bar linkages (triangles) BDE and GHI, which are rigid bodies while the crank rotates.
2. An upper and lower four-bar linkages (crank-rocker) N-M-B-J and N-M-C-K, whose analysis was done like any other crank-rocker mechanisms.
3. An open four-bar linkage D-C-F-G, also called parallel linkage because of its figurative resemblance to parallelogram.
4. The rigid three-bar linkage GHI is called the foot.
5. A ground, which is the link between the two pivoted fixed points (O_2 bar and O_4 bar), represented by vector n.
6. The interconnection point P of links H and I is called the toe.

Each leg is fixed at two points (O_2 bar and O_4 bar). Point O_4 bar is where the crank is pivoted to the ground and point O_2 bar is located at the connection of the upper rocker link B, the lower rocker link C, and the link D of the linkage BDE. Moreover, each two legs are joined at the point where the crank is fixed to the ground, which is at point O_4 bar. The two legs are out of phase with each other for one-half cycle of rotation of the crank.

The proposed design for the project consists of 4 legs, two on each side, instead of traditional 8 legs, four on each side. This change was made considering the project requirements and constrains. To drive the crank on each leg, single four-speed crank axle gearbox was used with a gear ratio of 126:1 giving the crank driving angular velocity of 105 rpm. These values only apply for maximum motor efficiency operating at 3 volts battery.

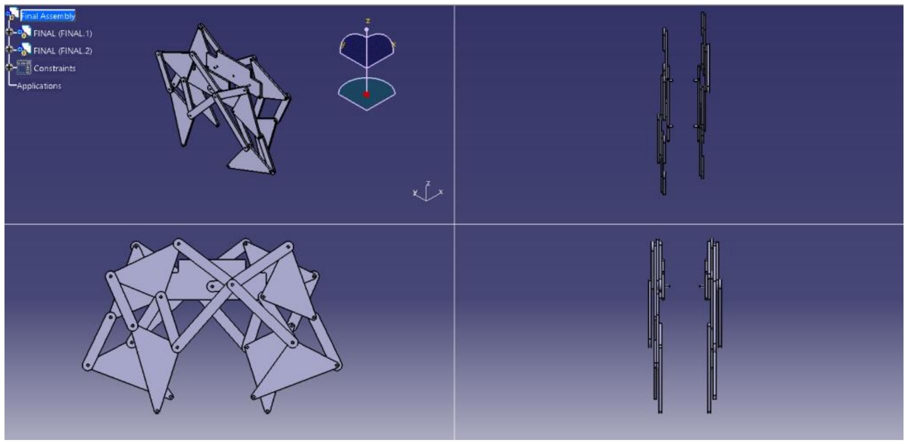


Figure 4 – Theo Jansen Legs Catia Model.

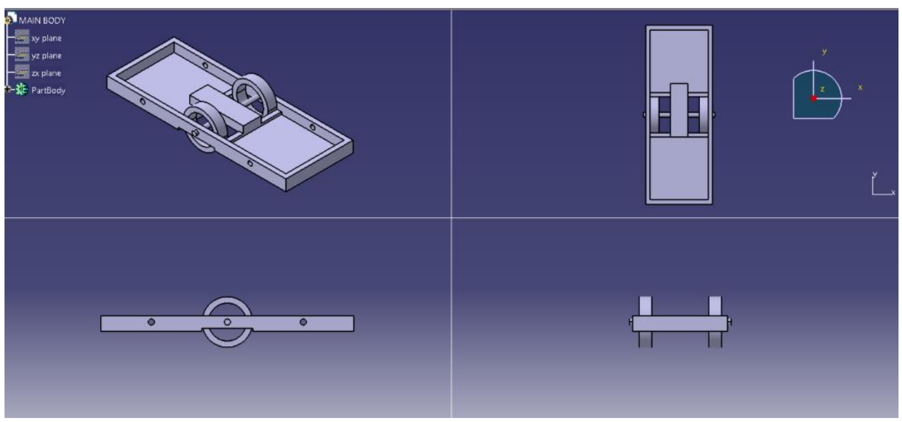


Figure 5 – Main Body Catia Model.

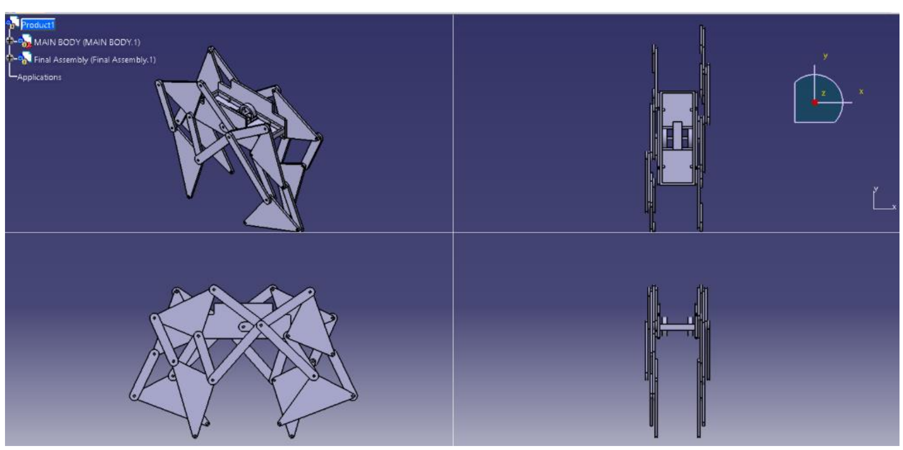


Figure 6 – Assembled Final Product Catia Model.

The above Figures illustrate the Catia model for the Theo Jansen Mechanism Robot, having top, side and front views of each main part. The main body is mounted with two 1.5 volts each AA battery and one four speed crank-axel gearbox having a DC electric motor of 12,300 rpm and torque of 585 g·cm.

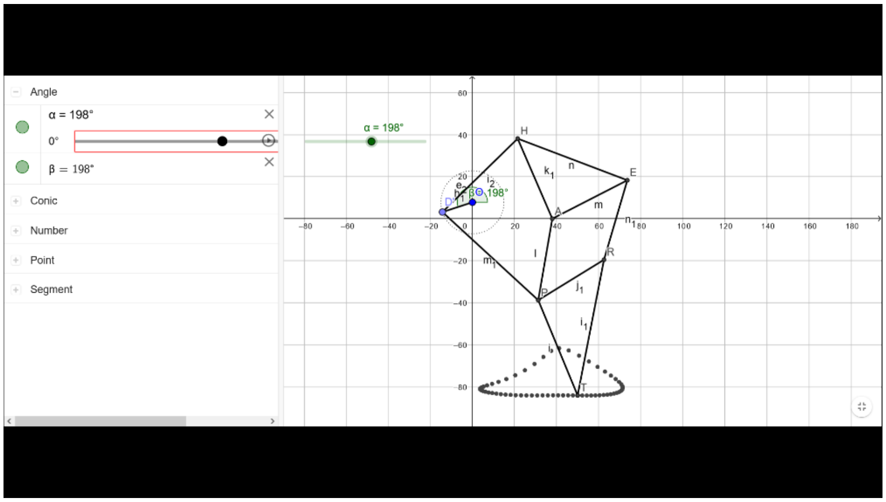


Figure 7 – GeoGebra Simulation of Theo Jansen Mechanism.

The above figure depicts the foot movement of the leg. The length of each link in the mechanism is defined to make the foot movement linear for one-half of the rotation of the crank. The remaining rotation of the crank allows the foot to raise to a predetermined height, which is called the height of step before returning to the starting position, which is the beginning of the next cycle.

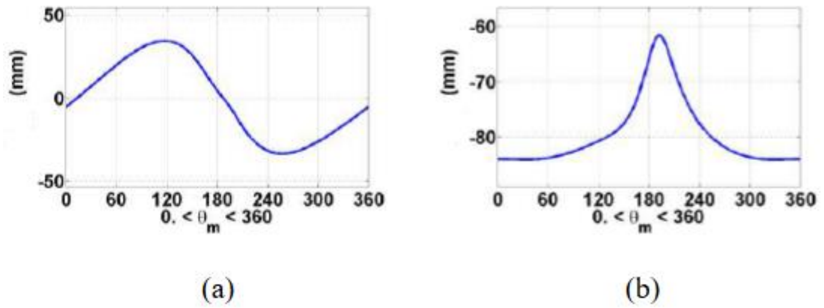
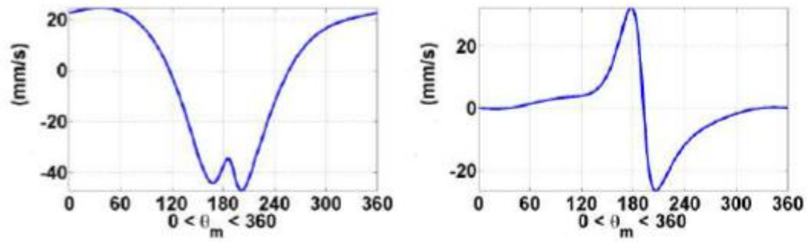
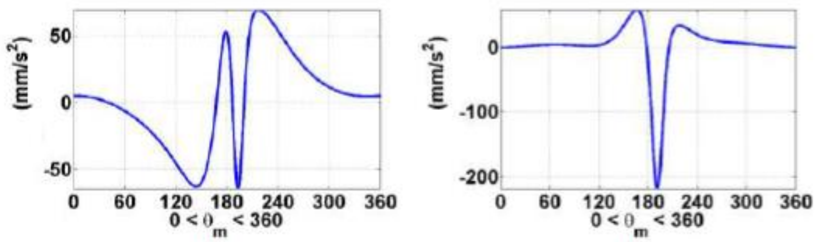


Figure 8 – Position analysis of point P (toe) for one rotation of crank. (a) X-Component. (b) Y-Component.



(a) (b)

Figure 9 – Linear Velocity analysis of point P (toe) for one rotation of crank. (a) X-Component. (b) Y-Component.



(a) (b)

Figure 10 – Linear Acceleration analysis of point P (toe) for one rotation of crank. (a) X-Component. (b) Y-Component.

The above figures illustrate the graph for distance, linear velocity and linear acceleration of point P (toe) on the leg. The readings were calculated for input crank angular velocity of 1 rad/s. The x-axis is represented be theta (input angle) which is directly proportional to time for 1 rotation. The calculated time for 1 rotation was 6.30 sec.

Design 3: Two-Leg Gear Mechanism

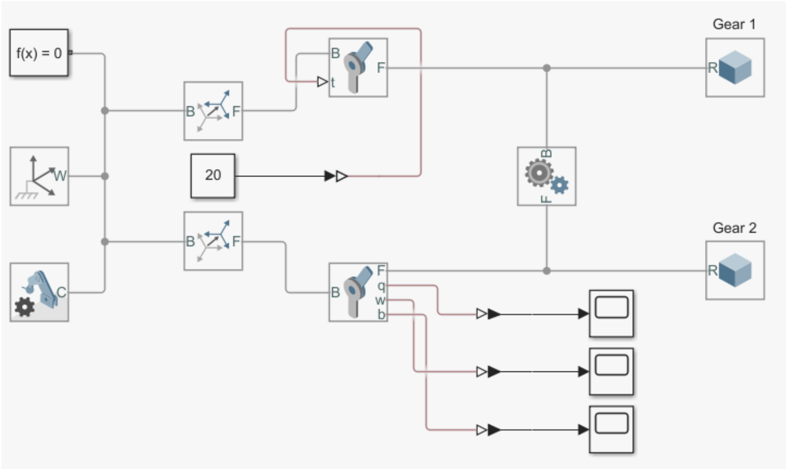


Figure 11 – MATLAB Simulink code for Two-leg Gear Mechanism.

As illustrated in the above picture, the MATLAB Simulink is simulated between two gears, the motor gear (input gear) and the driving gear (output gear). This approximation was made because, only the gear ratio of first and final gears are required to calculate the final angular velocity of the driving gear. Thus, simulating the motor gear and driving gear gives the same analysis as simulating the entire mechanism.

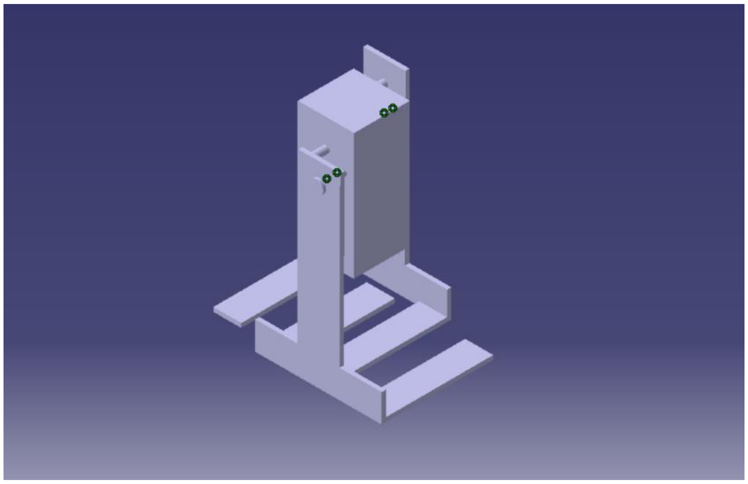


Figure 12 – Isometric view of the Two-Leg Design.

Figure 10 illustrates the two-leg robot design concept as a stationary object. When standing upright, the robot would be standing on two legs, positioned and aligned with the linkages in a way that the two legs do not clash. When in movement, the robot would ‘rest’ on one leg, but to keep the balance and not fall over, two prongs protrude out of each leg that reach almost as far as to the other side of the robot. This was stability can be maintained even when the robot’s centre of gravity is moving.

Table 2 – Two-Leg Gear Mechanism Measurements.

	Driving Gear	Input Gear
Diameter (D)	8 *cm*	2 *cm*
Number of Tooth (N)	64	16
Circular Pitch (CP)	π/8	π/8
Angular Velocity (ω)	26.25 *RPM*	105 *RPM*

The above calculations are based on gear ratio of 126:1 of the four-speed crank axel gearbox. The specific gear ratio was chosen keeping in mind the robot's output requirement, which was to be able to travel fast. This design can easily be made from ice-cream sticks and light cardboard, thus, making it very light but strong enough to support its internal structure. The angular speed from the driving gears is then used to find the robots linear velocity for a given leg length.

Design Selection

After conceptualizing all the designs and calculating everything, our team unanimously decided on finalizing Design 1. The frog mechanism was mainly chosen because of its extremely low cost, light weight, simple design, and relatively fast speed.

Table 3 – Final Design Metrics Evaluation

METRICS	Design 1	Design 2	Design 3
COST	**2**	**3**	**2**
MASS	**2**	**2**	**1**
MANUFACTURABILITY	**2**	**2**	**2**
SPEED	**2**	**1**	**2**
TOTAL	**8**	**8**	**7**

Design 2 was discarded, mainly because of the cost and difficulty to manufacture it. To make the necessary shapes needed for the Theo Jansen mechanism, a laser cutter would be needed since cutting by hand would be too difficult and very imprecise. This directly contributes to the increased cost as it is fairly expensive to operate a laser cutter and very specific material needs to be used for it – an MDF board. This, in turn, would also increase the mass of the robot and reduce the speed drastically, even when the optimal gear ratio is found. That is why, this design concept was discarded.

Design 3 was not selected due to the lack of its forward speed potential. The two-leg mechanism is fairly easy to manufacture, but it only has a small range of motion, which does not allow for adjustments in optimizing speed. Also, it would always need a front and back support, in order to make sure that the mechanism doesn't lose its balance and fall over. This makes the robot liable to fall while moving.

Final Design

Design Description

The cost of the frog design is very low compared to other design iterations because of the simplicity of the design and the choice of material that will be used to manufacture the mechanism. 3D printing object are relatively inexpensive, and due the dimension of the frog mechanism, the cost to print the overall mechanism would exceed approximately two dollars. The pins that would connect the linkages could be purchased on the market at low prices, due to the abundance of the item.

The mechanism was made from light weight material, allowing the mechanism to have small losses due to weight. The heavier an object is the more power in required to perform the same task when compared to a lighter weight object, the more power wasted on the bigger object will cause the overall efficiency of the system to decrease. The gearbox and motor materials had to remain the same as the initial material given to us by the producers of the product, thus allowing the design team to only change the material of the mechanism to a lightweight material to allow increased in efficiency.

The material used for the frog mechanism is very ductile and can withstand many high impact scenarios. ABS plastic requires 46MPa of force to be applied to deform into the plastic region, thus making the factor of safety high.

With the three main aspects of the frog mechanism, it was rated as the best score in manufacturability, inexpensiveness, and high resistance to fractures, compared to the other design iterations. The incredibly low weight and the high power of the frog mechanism design made the mechanism very fast. The gear ratios used were calculated to give the optimal performance between power (torque) and speed.

Design Methodology

The manufacturing process began with the assembly of the gearbox itself. According to the calculations, the optimal gear ratio configuration was the 126:1 ratio so that the output axle could spin at the fastest angular velocity possible.

Then began the design and manufacturing process of the casing for the gear box. As seen in figure 13, the side panels of the gearbox labelled as number 6 were manufactured out of a 3 mm thick MDF board that was cut using a laser cutter. The bottom panel labelled as number 5 in figure 13 was also laser cut from the same 3 mm MDF board. This would be the place on which the gearbox and the power source, which is the battery, would rest one. The gearbox and the battery are secured using Velcro strips attached on the bottom panel and on the gearbox. To make the two side panels stay secure and also not increase the weigh of the mechanism, a simple wire labelled as number 3 in figure 13 was made out of a paper clip and run through holes at the top of both side panels.

More holes are cut into the side panels, labelled as number 7 in figure 13. These holes are made to make way for the linkages that connect the casing side panels (number 6) to the moving parts labelled as number 1 and 2 in figure 13. The linkages (number 8) are connected to both panels using pins (number 7) and to make sure they move at the same speed and time, all the linkages are very carefully measured and aligned to reduce error in movement.

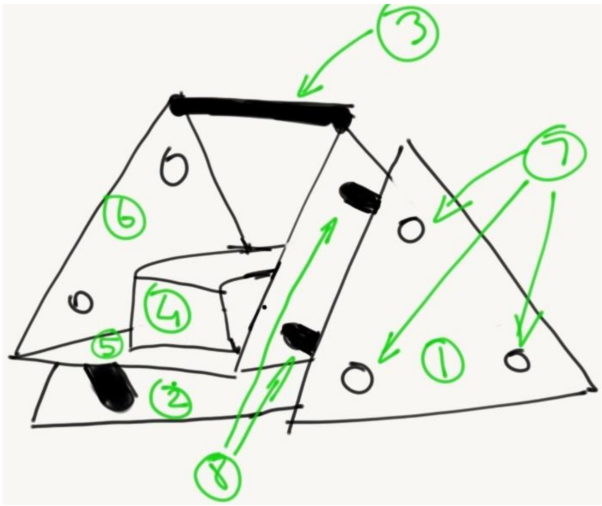


Figure 13 – Labelled Figure of the Frog Mechanism

Analysis

By applying velocity analysis on the output ternary linkage, the velocity of the frog mechanism could be found as the input angular velocity, all linkages lengths, all theta values, and their relationship are provided. The equation used to relate the input velocity to the output velocity is as follows:

$$v_4 = \frac{(w_2 \times r_2 \times sin(\theta_2 - \theta_3))}{(r_4 \times sin(\theta_4 - \theta_3))} \times r_4$$

Where v_4 is the velocity of the output link, w_2 is the angular velocity of the input link, r_2 is the length of the input link, θ_2 is the angle the input link makes with the x-axis, θ_3 is the angle of the coupler link with respect to the x-axis, r_4 is the length of the output link, and θ_4 is the angle the output links makes with the x-axis.

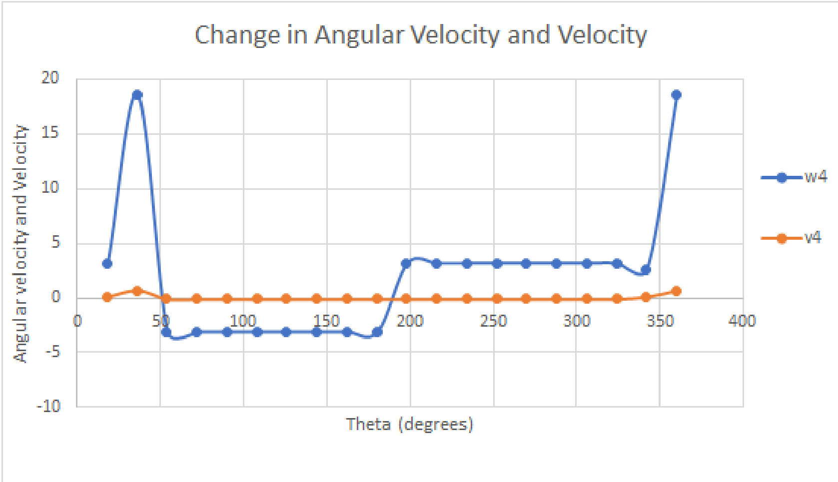
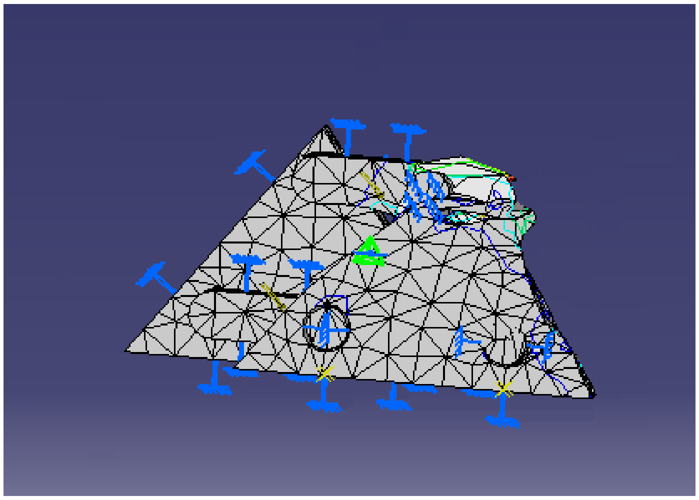


Figure 14 – Frog mechanism angular velocity and velocity relationship chart

The above figure is a chart representing the change in angular velocity and velocity the frog mechanism undergoes through during a 360 phase (i.e. a full rotation). The input angular velocity of the motor is constant and is dependent on the initial f.



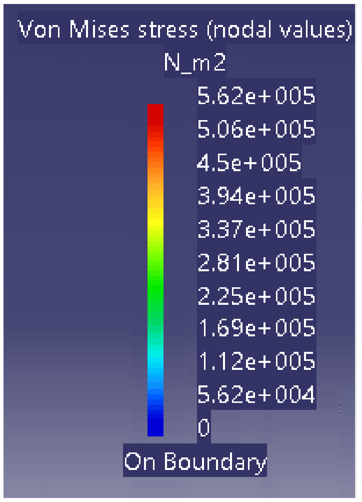


Figure 15 – Stress Analysis

Figure 16 – Stress Analysis Legend

As seen in the figure above, when the maximum tensile strength is applied to the from mechanism it will deform into the plastic region and alternate shape/form.

Conclusion

The design that would be implemented as the final and chosen design for the gearbox race competition was the frog mechanism due to the versatility it had, the overall increased efficiency, and high velocity. The frog mechanism was the most compact and easy to manufacture design as it needed minimal materials and had a simple design. The final dimensions of the frog mechanism were (30 × 15 × 20) mm, as this was the optimal size to maximize efficiency, reduce weight, and remain strong (i.e. not brittle). The mechanism would be made using a 3D printer that used ABS plastic filament. ABS plastic is a reliable ductile substance that is commonly used in mechanical applications, thus making it a good resource to use for the frog mechanism. The frog mechanism utilizes the rotations of the input and output links to displace. As seen in the appendix animation, the frog mechanism's output link would rotate from the back to the front, causing the gearbox to be lifted. At this stage the output link is in contact with the ground and is providing support to the lifted gearbox. As the rotation continues and the gearbox displace up and back down, it will travel 15mm, from its initial position. This process would repeat until the power runs out for the robot. This mechanism fulfills all the design objectives and constraints that were given by the design problem. The mechanism allows the gearbox to travel great distance relatively fast, with minimal power consumption. Also as shown from the graphs, the velocity analysis of the frog mechanism was the greatest making it the most desirable of all the designs as speed was the top ranked design objective that needed to be incorporated into the mechanism.

Workload Distribution Chart

Table 4 – Work Distribution Table

Team Member	**Adit Mistry**	**Aman Gilani**	**Ali Syed**
Work Distribution (%)	33	33	33

References

[1] A. G. Erdman and G. N. Sandor, Mechanism Design: Analysis and Synthesis - Fourth Edition, New Jersey: Prentice-Hall, Inc., 2001.

Appendix I: MATLAB Code

FROG MECHANISM:

```
%403 Final Project MATLAB
%Frog Mechanism
clear
clc

r1 = 30;
r2 = 35;
r3 = 30;
r4 = 35;

% set up for animation
figure
axis([-40 65 -40 55])
pbaspect([1 1 1])

% angles
theta_2 = deg2rad(0:20:1080);  % 1080 is 360*3 due to it rotating 3
times

% loop

for i = 1:55
   phi_4(i) = acos((r3^2 + r4^2 - r1^2 - r2^2 +
2*r1*r2*cos(theta_2(i)))/(2*r3*r4));

   BD = sqrt(r1^2 + r2^2 - 2*r1*r2*cos(theta_2(i)));% Cosine law with
the provided angle of theta_2.

   phi_31 = asin(sin(theta_2(i))*r1/BD);
   phi_32 = asin(sin(phi_4(i))*r4/BD);
   phi_3(i) = phi_31 + phi_32;
   theta_3(i) = phi_3(i) - pi + theta_2(i);

   theta_4 = -phi_4(i);
   w2 = ((105*2*pi)/60); %In rad/s

            w4 = ((w2*r2*sin(theta_2(i)-theta_3(i)))/(r4*sin(theta_4-
theta_3(i))));
            display (w4);
            v4 = w4*r4/1000;
            display(v4);

   zz(1,:) = [0,0];
   zz(2,:) = [r2*cos(theta_2(i)), r2*sin(theta_2(i))];
   zz(3,:) = [r1 + r4*cos(theta_2(i)), r4*sin(theta_2(i))];
   zz(4,:) = [r1 0];
   zz(5,:) = [0 0];
   zz(6,:) = [r2*cos(theta_2(i)),r2*sin(theta_2(i))];
   zz(7,:) = [r3/2 + r2*cos(theta_2(i)), r2/2 + r2*sin(theta_2(i))];
   zz(8,:) = [r1 + r4*cos(theta_2(i)), r4*sin(theta_2(i))];
   zz(9,:) = [r1 0];
```

```
    zz(10,:) = [r1/2, r2/2];
    zz(11,:) = [0 0];
    zz(12,:) = [r1/2, r2/2];
    zz(13,:) = [r3/2 + r2*cos(theta_2(i)), r2/2 + r2*sin(theta_2(i))];

    grid on
    plot(zz(:,1), zz(:,2), 'dr-')
    axis([-40 65 -40 55])
    title('4-bar linkage');
    xlabel('x distance');
    ylabel('y distance');

    pause (0.5)
end
```

THEO JANSEN MECHANISM

```
%AER 403 FINAL PROJECT
%THEO JANSEN MECHANISM
clear all; clc; close all;

%% Angles and Distances.
L1=6; L2=1; L3=8; L33=8; L4=5; L44=5; L5=5; L6=5; L66=9;
L7=5; L8=.5;
A1=0; A2=pi/2:0.3:6*pi+(pi/2);
A22=pi+A2;
A2=-A2; A22=-A22;

%% Position Analysis.
Bx=L2.*cos(A2);
By=L2.*sin(A2);
B2x=L2.*cos(A22);
B2y=L2.*sin(A22);
[A3,A4]=Mechanism(L1,L2,L3,L4,A1,A2,'cross');
A5=(pi-A4)+(pi/2);
[A32,A42]=Mechanism(L1,L2,L3,L4,A1,A22,'cross');
A52=(pi-A42)+(pi/2);
Cx=Bx+(L3.*cos(A3));
Cy=L4.*sin(A4);
C2x=B2x+(L3.*cos(A32));
C2y=L4.*sin(A42);
Ex=L1;    Ey=-L8;
j=2.*L4.*((L1.*cos(A1))-(L2.*cos(A2)));
k=2.*L4.*((L1.*sin(A1))-(L2.*sin(A2)));
m=(L1.^2)+(L2.^2)-(L33.^2)+(L44.^2)-(2.*L1.*L2.*cos(A1-
A2));
A44=2.*atan((-k+sqrt((j.^2)+(k.^2)-(m.^2)))./(m-j));
n=2.*L3.*((L2.*cos(A2))-(L1.*cos(A1)));
p=2.*L3.*((L2.*sin(A2))-(L1.*sin(A1)));
```

```
q=(L1.^2)+(L2.^2)+(L33.^2)-(L44.^2)-(2.*L1.*L2.*cos(A2-
A1));
A33=2.*atan((-p-sqrt((n.^2)+(p.^2)-(q.^2)))./(q-n));
j2=2.*L4.*((L1.*cos(A1))-(L2.*cos(A22)));
k2=2.*L4.*((L1.*sin(A1))-(L2.*sin(A22)));
m2=(L1.^2)+(L2.^2)-(L33.^2)+(L44.^2)-(2.*L1.*L2.*cos(A1-
A22));
A442=2.*atan((-k2+sqrt((j2.^2)+(k2.^2)-(m2.^2)))./(m2-j2));
n2=2.*L3.*((L2.*cos(A22))-(L1.*cos(A1)));
p2=2.*L3.*((L2.*sin(A22))-(L1.*sin(A1)));
q2=(L1.^2)+(L2.^2)+(L33.^2)-(L44.^2)-(2.*L1.*L2.*cos(A22-
A1));
A332=2.*atan((-p2-sqrt((n2.^2)+(p2.^2)-(q2.^2)))./(q2-n2));
Dx=Ex+L5.*cos(pi-A5);
Dy=Ey+L5.*sin(pi-A5);
D2x=Ex+L5.*cos(pi-A52);
D2y=Ey+L5.*sin(pi-A52);
A5=-A5;    A4=-A4;
[A6,A7]=Mechanism(L5,L4,L6,L7,A5,A4,'cross');
A52=-A52;    A42=-A42;
[A62,A72]=Mechanism(L5,L4,L6,L7,A52,A42,'cross');
Fx=Bx+(L33.*cos(A33));
Fy=By+L33.*sin(A33);
F2x=B2x+(L33.*cos(A332));
F2y=B2y+L33.*sin(A332);
Gx=Fx-L6.*cos(A6);
Gy=Fy-L6.*sin(A6);
G2x=F2x-L6.*cos(A62);
G2y=F2y-L6.*sin(A62);
Hx=Fx+L66.*cos(A6+(pi/2));
Hy=Fy+L66.*sin(A6+(pi/2));
H2x=F2x+L66.*cos(A62+(pi/2));
H2y=F2y+L66.*sin(A62+(pi/2));
BBx=-L2.*cos(A2);
BBy=L2.*sin(A2);
BB2x=-L2.*cos(A22);
BB2y=L2.*sin(A22);
CCx=BBx-(L3.*cos(A3));
CCy=-L4.*sin(A4);
CC2x=B2x-(L3.*cos(A32));
CC2y=-L4.*sin(A42);
EEx=-L1;    EEy=-L8;
DDx=EEx-L5.*cos(pi-A5);
DDy=EEy-L5.*sin(pi-A5);
DD2x=EEx-L5.*cos(pi-A52);
DD2y=EEy-L5.*sin(pi-A52);
FFx=BBx-(L33.*cos(A33));
```

```
FFy=BBy+L33.*sin(A33);
FF2x=BB2x-(L33.*cos(A332));
FF2y=BB2y+L33.*sin(A332);
GGx=FFx+L6.*cos(A6);
GGy=FFy-L6.*sin(A6);
GG2x=FF2x+L6.*cos(A62);
GG2y=FF2y-L6.*sin(A62);
HHx=FFx-L66.*cos(A6+(pi/2));
HHy=FFy+L66.*sin(A6+(pi/2));
HH2x=FF2x-L66.*cos(A62+(pi/2));
HH2y=FF2y+L66.*sin(A62+(pi/2));

%% Velocity Analysis
A4=-A4;  A5=-A5;
W2=105;  % Angular velocity of the crank in rad/s
W3=-(L2.*W2.*sin(A2-A4))./(L3.*sin(A3-A4));
W4=(L2.*W2.*sin(A2-A3))./(L4.*sin(A4-A3));
W5=W4;
W33=-(L2.*W2.*sin(A2-A44))./(L33.*sin(A33-A44));
W44=(L2.*W2.*sin(A2-A33))./(L44.*sin(A44-A33));
A4=-A4;  A5=-A5;
W6=(L5.*W5.*sin(A5-A7)-L44.*W44.*sin(A44-A7))./(L6.*sin(A6-
A7));
W7=(L44.*W44.*sin(A44)-
L5.*W5.*sin(A5)+L6.*W6.*sin(A6))./(L7.*sin(A7));

%% Acceleration Analysis
A4=-A4;  A5=-A5;
Alf2=0;    % Angular acceleration of the crank
Alf3=((L2.*(W2.^2).*cos(A2-A4))+(L3.*(W3.^2).*cos(A3-A4))-
(L4.*(W4.^2))-(L2.*sin(A4-A2)))./(L3.*sin(A4-A3));
Alf4=((L2.*Alf2.*sin(A3-A2))-(L2.*(W2.^2).*cos(A2-A3))-
(L3.*(W3.^2))+(L4.*(W4.^2).*cos(A4-A3)))./(L4.*sin(A3-A4));
Alf5=Alf4;
Alf33=((L2.*(W2.^2).*cos(A2-A44))+(L33.*(W33.^2).*cos(A33-
A44))-(L44.*(W44.^2))-(L2.*sin(A44-A2)))./(L33.*sin(A44-
A33));
Alf44=((L2.*Alf2.*sin(A33-A2))-(L2.*(W2.^2).*cos(A2-A33))-
(L33.*(W33.^2))+(L44.*(W44.^2).*cos(A44-
A33)))./(L44.*sin(A33-A44));
A4=-A4;  A5=-A5;
Alf7=((L44.*Alf44.*sin(A44-A6))+(L44.*(W44.^2).*cos(A44-
A6))+(L6.*(W6.^2))-(L5.*Alf5.*sin(A5-A6))-
(L5.*(W5.^2).*cos(A5-A6))-(L7.*(W7.^2).*cos(A7-
A6)))./(L7.*sin(A7-A6));
Alf6=((L5.*Alf5.*sin(A5-A7))+(L5.*(W5.^2).*cos(A5-
A7))+(L7.*(W7.*2))-(L44.*Alf44.*sin(A44-A7))-
```

```
(L44.*(W44.^2).*cos(A44-A7))-(L6.*(W6.^2).*cos(A6-
A7)))./(L6.*sin(A6-A7));
A4=-A4;  A5=-A5;

end
```

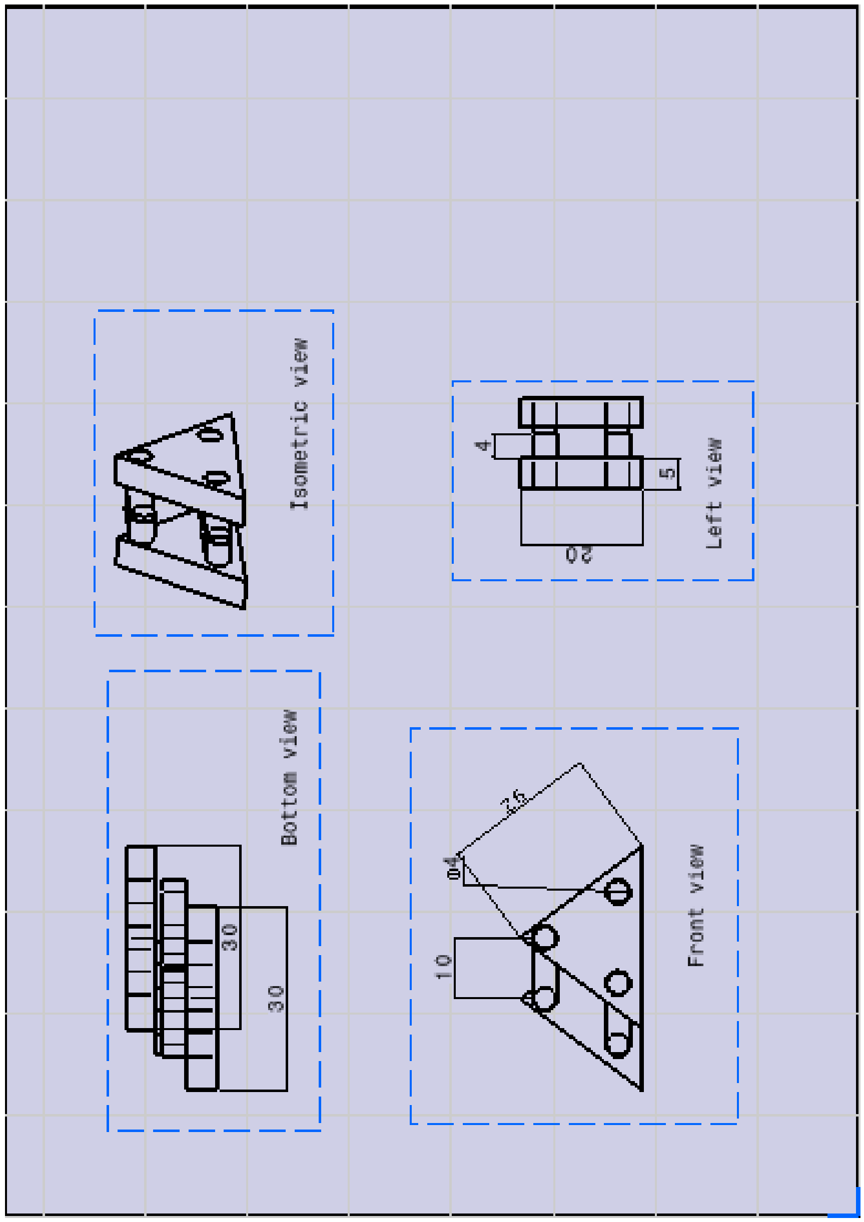


Figure 15 – Frog Mechanism Views