ME748: Computer Aided Simulation of Machines

Term Project 1: Kinematic Analysis

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Abstract

In this term project I created a (virtual) model and simulated the mechanism chosen in Assignment 1 using a mechanism simulation software Adams. The model is be used to generate displacement, velocity and acceleration curves of the important components of the machine. The model has been validated against some theoretical (manual) calculations. These details have been compiled in the form of the following report.

Contents

1 Model Specification

1.1 Pictorial Depiction

Chain drives and shafts combined have been modelled as thick round gears.

Fig. 1: Actual mechanism

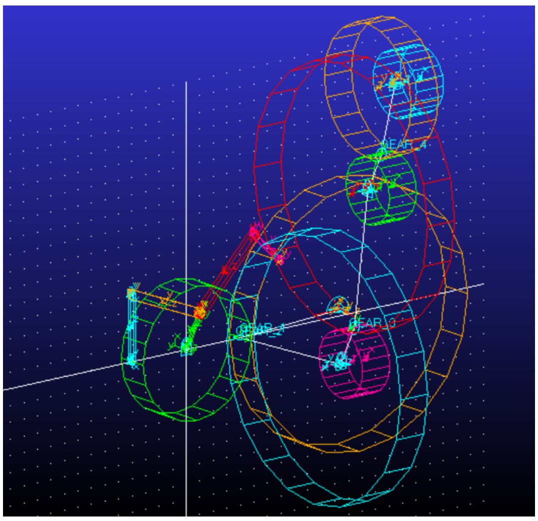


Fig. 2: Model mechanism

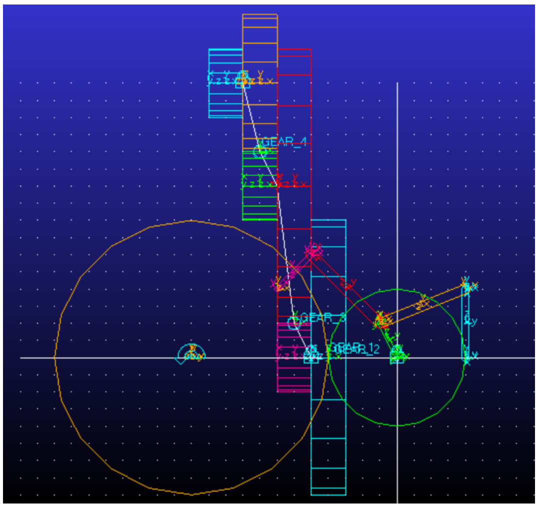


Fig. 3: Front View of Model mechanism

1.2 Geometry and Material

1.2.1 Dimensions of every component

All geometrical details required to create the model. These are indicated in figures 4-16.

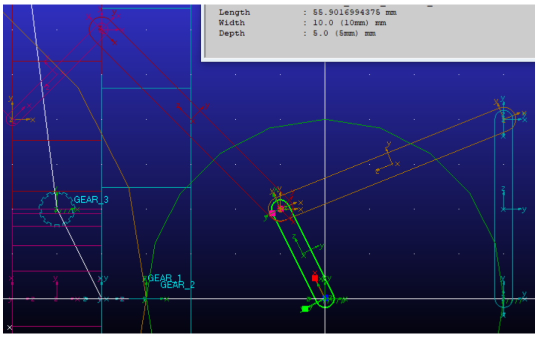


Fig. 4: Dimensions of Part 8

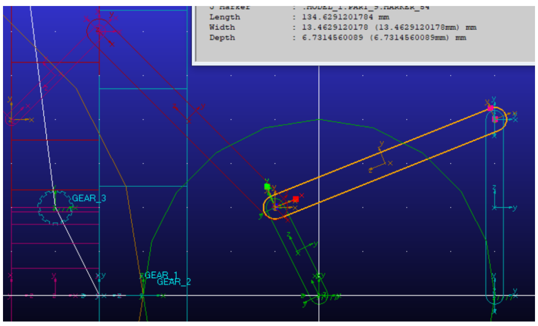


Fig. 5: Dimensions of Part 9

1.2.2 Masses of every component

1. Part 8: 2.4817759832E-02 kg
2. Part 9: 0.1025310773 kg

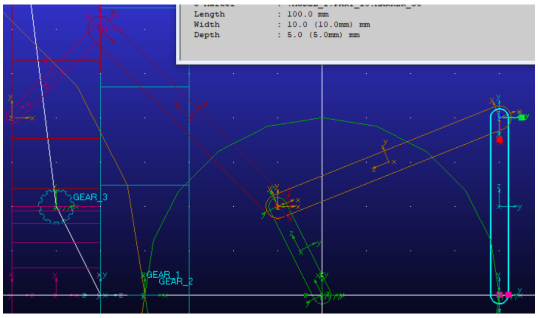


Fig. 6: Dimensions of Part 10

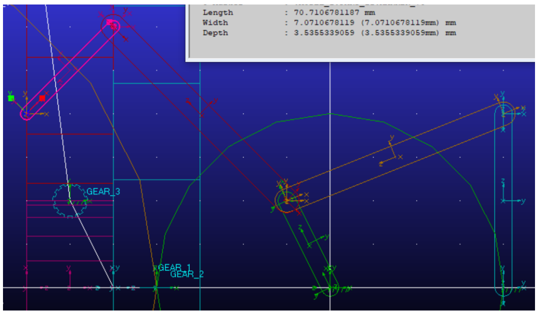


Fig. 7: Dimensions of Part 11

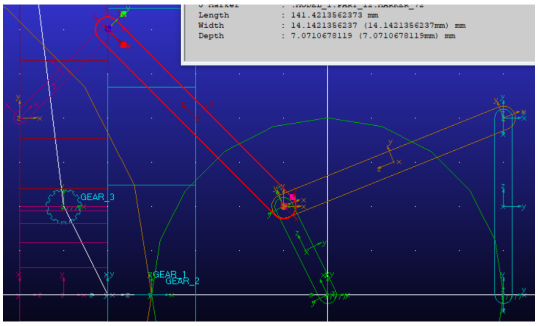


Fig. 8: Dimensions of Part 12

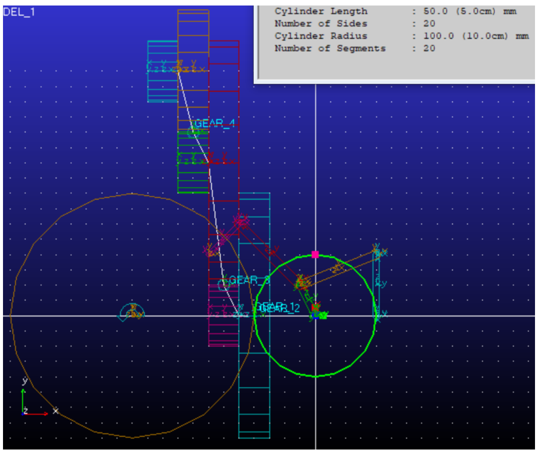


Fig. 9: Dimensions of Part 13

3. Part 10: 0.1025310773 kg
4. Part 11: 1.4855713127E-02 kg

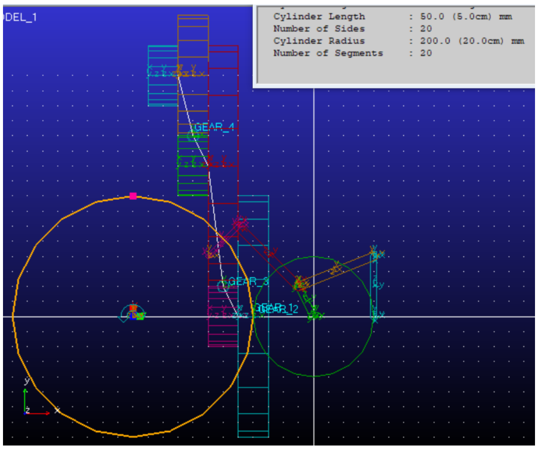


Fig. 10: Dimensions of Part 14

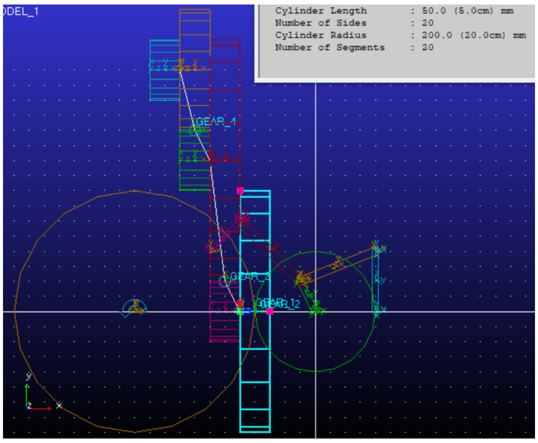


Fig. 11: Dimensions of Part 15

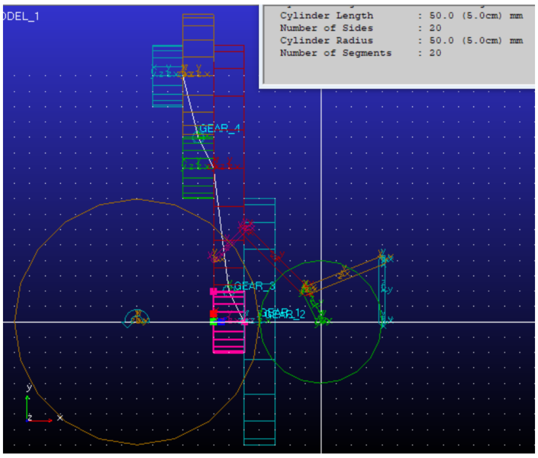


Fig. 12: Dimensions of Part 16

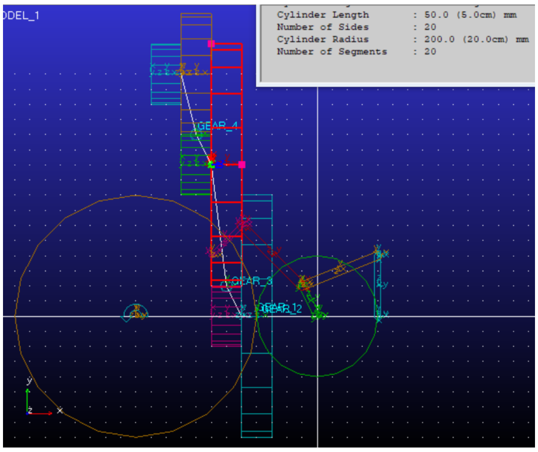


Fig. 13: Dimensions of Part 17

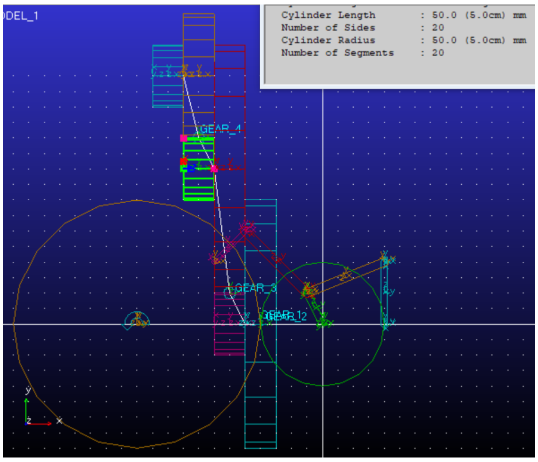


Fig. 14: Dimensions of Part 18

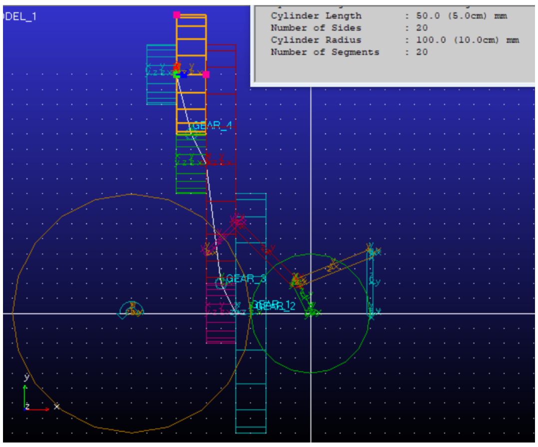


Fig. 15: Dimensions of Part 19

5. Part 12: 0.118845705 kg
6. Part 13: 12.2537821453 kg
7. Part 14: 49.0151285813 kg
8. Part 15: 49.0151285813 kg
9. Part 16: 3.0634455363 kg
10. Part 17: 49.0151285813 kg
11. Part 18: 3.0634455363 kg
12. Part 19: 12.2537821453 kg
13. Part 20: 3.0634455363 kg

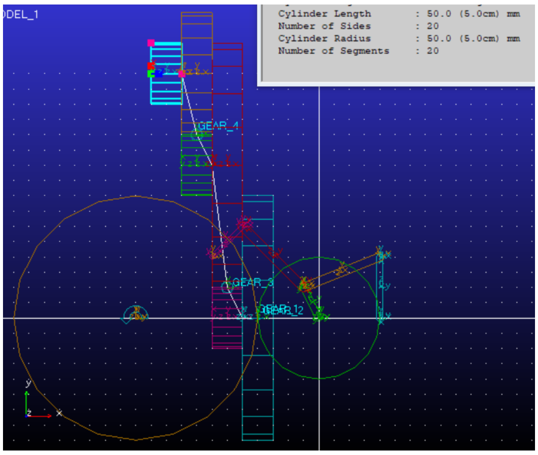


Fig. 16: Dimensions of Part 20

1.2.3 Moments of inertia of every component

1. Part 8:
   IXX : 8.6056563943 kg-mm**2
   IYY : 8.4571303608 kg-mm**2
   IZZ : 0.251933366 kg-mm**2

2. Part 9:
   IXX : 181.4828571273 kg-mm**2
   IYY : 180.3504960967 kg-mm**2
   IZZ : 1.9066842627 kg-mm**2

3. Part 10:
   IXX : 41.0336896795 kg-mm**2
   IYY : 40.7776602573 kg-mm**2
   IZZ : 0.4311056795 kg-mm**2

4. Part 11:
   IXX : 7.2538000573 kg-mm**2
   IYY : 7.2085400222 kg-mm**2
   IZZ : 7.6209437369E-02 kg-mm**2

5. Part 12:
   IXX : 232.1216018363 kg-mm**2
   IYY : 230.6732807113 kg-mm**2
   IZZ : 2.4387019949 kg-mm**2

6. Part 13:
   IXX : 6.1268910727E+04 kg-mm**2
   IYY : 3.3187326644E+04 kg-mm**2
   IZZ : 3.3187326644E+04 kg-mm**2

7. Part 14:
   IXX : 9.8030257163E+05 kg-mm**2
   IYY : 5.0036277093E+05 kg-mm**2
   IZZ : 5.0036277093E+05 kg-mm**2

8. Part 15:
   IXX : 9.8030257163E+05 kg-mm**2
   IYY : 5.0036277093E+05 kg-mm**2
   IZZ : 5.0036277093E+05 kg-mm**2

9. Part 16:
   IXX : 3829.3069204147 kg-mm**2
   IYY : 2552.8712802765 kg-mm**2
   IZZ : 2552.8712802765 kg-mm**2

10. Part 17:
    IXX : 9.8030257163E+05 kg-mm**2
    IYY : 5.0036277093E+05 kg-mm**2
    IZZ : 5.0036277093E+05 kg-mm**2

11. Part 18:
    IXX : 3829.3069204147 kg-mm**2
    IYY : 2552.8712802765 kg-mm**2
    IZZ : 2552.8712802765 kg-mm**2

12. Part 19:
    IXX : 6.1268910727E+04 kg-mm**2
    IYY : 3.3187326644E+04 kg-mm**2
    IZZ : 3.3187326644E+04 kg-mm**2

13. Part 20:
    IXX : 3829.3069204147 kg-mm**2
    IYY : 2552.8712802765 kg-mm**2
    IZZ : 2552.8712802765 kg-mm**2

1.3 Constraints

Constrains on the motion of each component. (May require details of the joints.)

There are mainly three types of joints in my mechanism. Hinge joint, gear joint and locking constraint. The chain drives in the original mechanism have also been modelled as gear joints. That is the reason the gears are so bulky to include the inertial of the shafts as well.

1. Hinge Joint: Between parts 8-9, 9-10, 10-Ground, between all gears and ground.

2. Gear Joint: Between parts every two cylinder (which is modelled as pitch circle of the gears). Parts 13-14, 14-15, 16-17, 18-19.

3. Lock joint: Parts 11-12, 12-9, 8-13 and for gear trains 15-16, 17-18, 19-20.

1.4 Motion Transmission

1.4.1 Driving Component

The driving component is the engine which goes in the gear box to increase torque and reduce angular velocity which is attached to the gear shown by part 14 which moves at 30 deg per sec of angular velocity.

1.4.2 Component which gives output of interest

The output is given by the links 11 and 12 which are attached to the coupler of the 4-bar mechanism which is responsible for producing the motion to pickup the seedling from the tray and plant it in the ground.

The tray is moved by a chain drive which is attached to the gear/part 20 so that it plants 16 seedlings in a row then changes direction to plant from the next row and so on.

2 Kinematic Simulation

This section contains the plots of simulated kinematic parameters (i.e. displacement, velocity and acceleration) for the output component. The independent axis is either Time or Motion of the input link.

2.1 Output Component

2.1.1 Simulated and Expected displacement profile

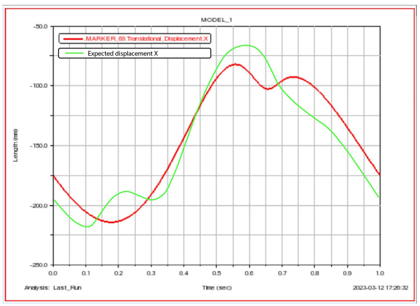


Fig. 17: X displacement vs time

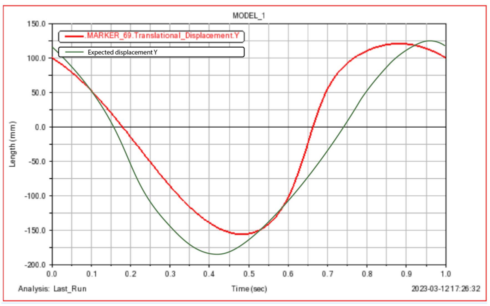


Fig. 18: Height (Y) vs time

2.1.2 Simulated and Expected velocity profile

2.1.3 Simulated and Expected acceleration profile

2.1.4 Comments

Explaining the dissimilarity between simulated and expected plots if any.

1. The slight dissimilarity between the simulated and expected displacement is due to various reasons.

2. The chain drives have been approximated to be large gears.

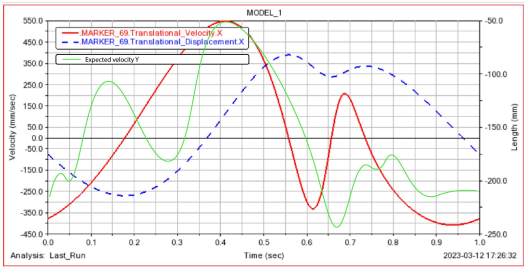


Fig. 19: X Velocity vs time

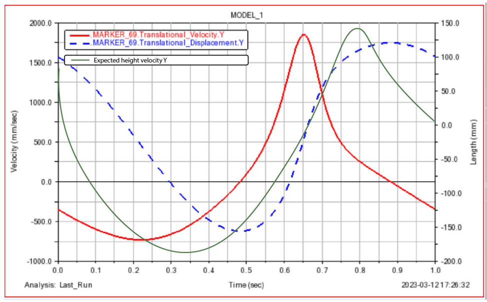


Fig. 20: Y Velocity vs time

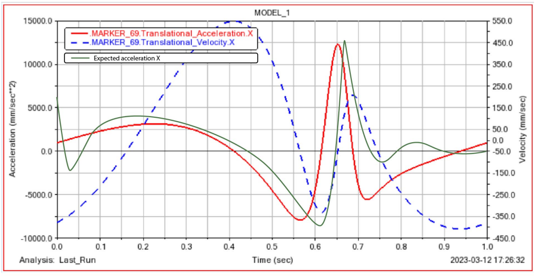


Fig. 21: X Acceleration cs time

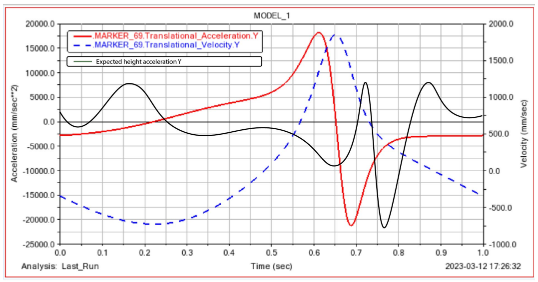


Fig. 22: Y Acceleration vs time

3. Expected graph assumes non circular gears made for desired output trajectory, but in most of the mechanisms and my mechanism used a 4-bar mechanism at the end to generate similar trajectory with part of the coupler as the output.

4. The error in velocity profiles builds up from the displacement profile by differentiation. Due to

discrete time differentiation we know that the error due to noise increases rapidly. So it is possible that the expected values have noise.

5. Similar explanation goes for acceleration error.

6. The error also comes from different dimensions assumed during modelling of the mechanism as certain dimensions from the original mechanism were unknown.

2.2 Sensitivity Analysis

Study of the sensitivity of the kinematic parameters of the output component to small changes in the dimensions (e.g. link lengths) of the two other components. The additional graphs with the modified components which were used for performing this sensitivity analysis is shown along with the original graphs.

2.3 Analysis of joint clearance

Introducing a clearance in one of the joints and simulating the mechanism to run at normal speed and at higher speed.

2.3.1 Normal speed

2.3.2 Higher speed

3 Validation of kinematic simulation

3.1 Theoretical evaluation of kinematic parameters

In this section, the displacement, velocity and acceleration of the output component is evaluated manually at four positions of the input link separated by 90 degrees.

These are displayed in fig 23, fig 24, fig 25 fig 26 and MATLAB script is attached in fig 27.

3.2 Comparison of kinematic parameters

3.2.1 Displacement

The four values of displacement evaluated in section 3.1 superimposed in the plot of section 2.1.1. Refer fig 23, fig 24 and fig 25 for displacement calculation analytically.

For superimposed graphs refer fig 28 and fig 29.

3.2.2 Velocity

The four values of velocity evaluated in section 3.1 superimposed in the plot of section 2.1.2. Refer fig 26 for analytical velocity result.

For superimposed graphs refer fig 30 and fig 31.

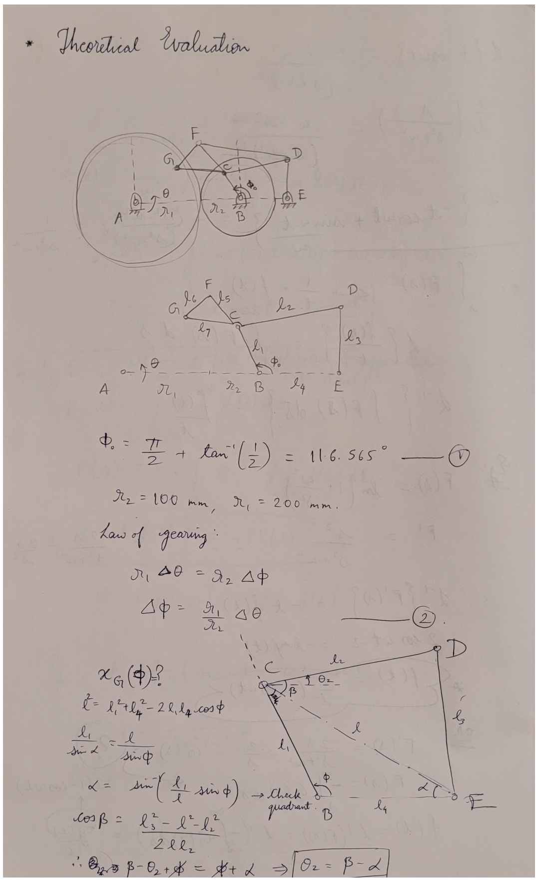


Fig. 23: Theoretical evaluation page 1

3.2.3 Acceleration

The four values of velocity evaluated in section 3.1 superimposed in the plot of section 2.1.3. Refer fig 26 for analytical acceleration result.

For superimposed graphs refer fig 32 and fig 33.

3.2.4 Comments

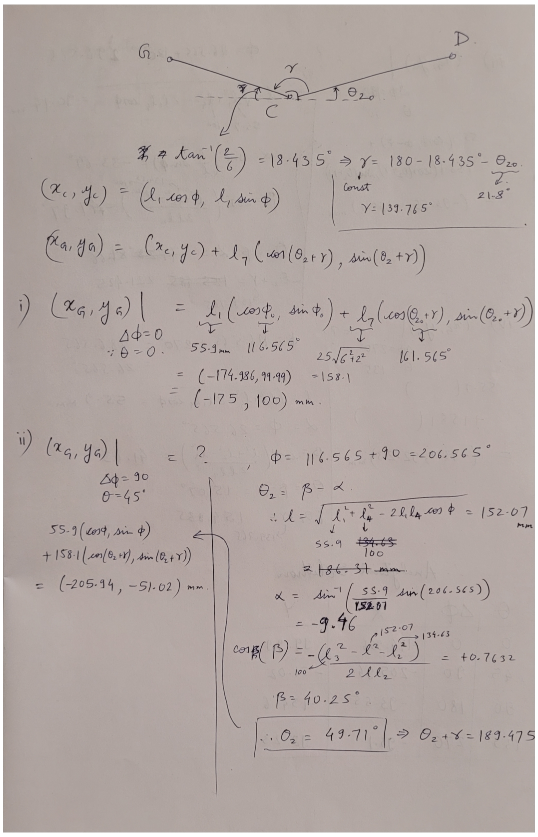
1. There are minor differences in the calculations which can be due to two reasons.

2. First being the rounding error while taking the values in MATLAB.

3. Second being the simulation error where number of steps were a little low for generating these inaccuracies.

References

[1] Liang Sun, Xuan Chen, Chuanyu Wu, Guofeng Zhang, Yadan Xu, *Synthesis and design of rice pot seedling transplanting mechanism based on labeled graph theory*, Computers and Electronics in Agriculture, Vol. 143, 2017, Pages 249-261, ISSN 0168-1699, https://doi.org/10.1016/j.compag.2017.10.021


G D

γ C θ_{20}

$\tan^{-1}\left(\frac{2}{6}\right) = 18.435^\circ \Rightarrow \gamma = 180 - 18.435^\circ - \theta_{20}$, $\theta_{20} = 21.8^\circ$, const $\gamma = 139.765^\circ$

$(x_c, y_c) = (l_1 \cos\phi,\ l_1 \sin\phi)$

$(x_G, y_G) = (x_c, y_c) + l_7(\cos(\theta_2+\gamma), \sin(\theta_2+\gamma))$

i) $(x_G, y_G)\big|_{\Delta\phi=0,\ \theta=0} = l_1(\cos\phi_0, \sin\phi_0) + l_7(\cos(\theta_{20}+\gamma), \sin(\theta_{20}+\gamma))$

$l_1 = 55.9$ mm, $\phi_0 = 116.565^\circ$, $l_7 = 25\sqrt{6^2+2^2} = 158.1$, $\theta_{20}+\gamma = 161.565^\circ$

$= (-174.986, 99.99)$

$= (-175, 100)$ mm.

ii) $(x_G, y_G)\big|_{\Delta\phi=90,\ \theta=45^\circ} = ?$, $\phi = 116.565 + 90 = 206.565^\circ$

$\theta_2 = \beta - \alpha$

$\therefore l = \sqrt{l_1^2 + l_4^2 - 2l_1l_4\cos\phi} = 152.07$ mm ($l_1 = 55.9$, $l_4 = 100$)

$\alpha = \sin^{-1}\left(\frac{55.9}{152.07}\sin(206.565)\right) = -9.46$

$\cos(\beta) = \frac{-(l_3^2 - l^2 - l_2^2)}{2ll_2} = +0.7632$

$\beta = 40.25^\circ$

$\boxed{\therefore \theta_2 = 49.71^\circ} \Rightarrow \theta_2 + \gamma = 189.475$

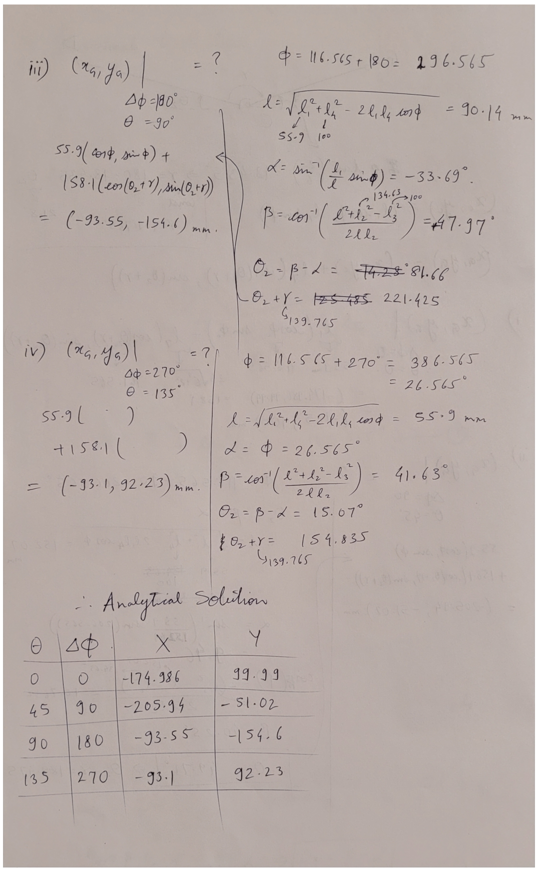
$55.9(\cos\phi, \sin\phi) + 158.1(\cos(\theta_2+\gamma), \sin(\theta_2+\gamma))$

$= (-205.94, -51.02)$ mm

Fig. 24: Theoretical evaluation page 2

[2] Yadav, Dr & Mital, Patel & P, Shukla & Pund, Sahastrarashmi. (2007). *Ergonomic evaluation of manually operated six-row paddy transplanter.* International Agricultural Engineering Journal. 16. 147-157.

[3] Guru, Prabhat & Chhuneja, Naresh & Dixit, Anoop & Tiwari, Prem & Kumar, Anjani. (2018). *Mechanical transplanting of rice in India: Status, technological gaps and future thrust.* ORYZA- An International Journal on Rice. 55. 10.5958/2249-5266.2018.00012.7.


iii) $(x_G, y_G)\big|_{\Delta\phi=180^\circ,\ \theta=90^\circ} = ?$, $\phi = 116.565 + 180 = 296.565$

$l = \sqrt{l_1^2 + l_4^2 - 2l_1l_4\cos\phi} = 90.14$ mm

$\alpha = \sin^{-1}\left(\frac{l_1}{l}\sin\phi\right) = -33.69^\circ$

$\beta = \cos^{-1}\left(\frac{l^2 + l_2^2 - l_3^2}{2ll_2}\right) = 47.97^\circ$

$\theta_2 = \beta - \alpha = 81.66$

$\theta_2 + \gamma = 221.425$

$55.9(\cos\phi, \sin\phi) + 158.1(\cos(\theta_2+\gamma), \sin(\theta_2+\gamma))$

$= (-93.55, -154.6)$ mm.

iv) $(x_G, y_G)\big|_{\Delta\phi=270^\circ,\ \theta=135^\circ} = ?$, $\phi = 116.565 + 270^\circ = 386.565 = 26.565^\circ$

$l = \sqrt{l_1^2 + l_4^2 - 2l_1l_4\cos\phi} = 55.9$ mm

$\alpha = \phi = 26.565^\circ$

$\beta = \cos^{-1}\left(\frac{l^2 + l_2^2 - l_3^2}{2ll_2}\right) = 41.63^\circ$

$\theta_2 = \beta - \alpha = 15.07^\circ$

$\theta_2 + \gamma = 154.835$

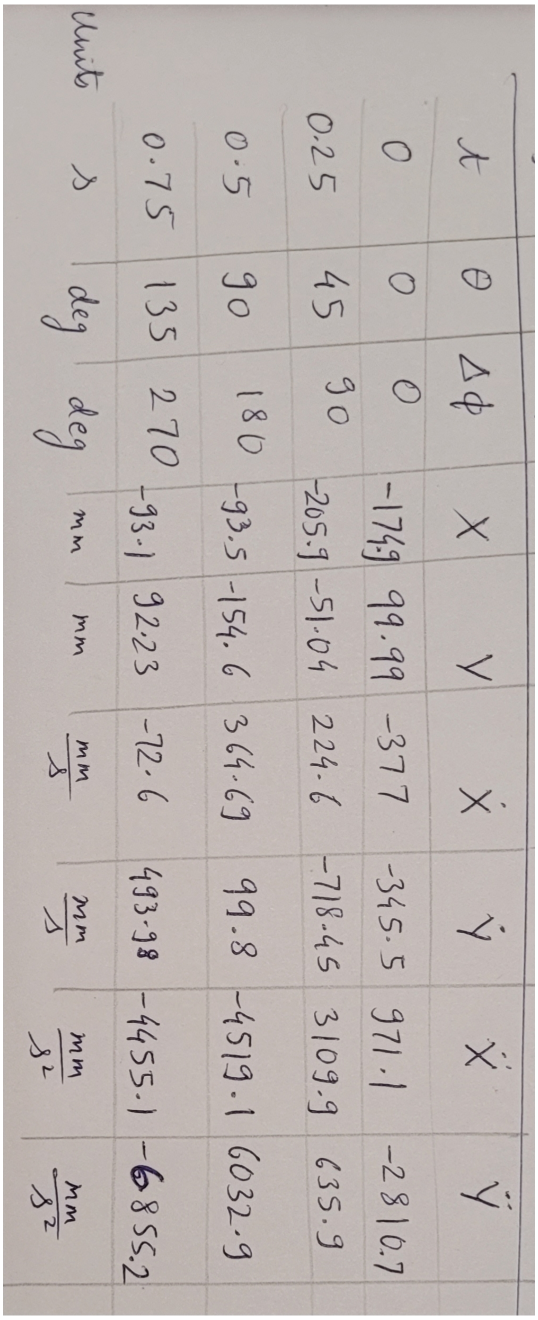
$55.9(\ \ ) + 158.1(\ \ )$

$= (-93.1, 92.23)$ mm.

$\therefore$ Analytical Solution

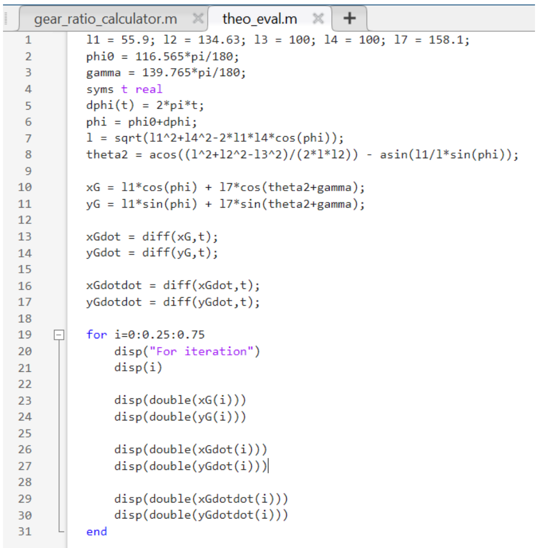
θ	$\Delta\phi$	X	Y
0	0	-174.986	99.99
45	90	-205.94	-51.02
90	180	-93.55	-154.6
135	270	-93.1	92.23

Fig. 25: Theoretical evaluation page 3



t	θ	Δφ	X	Y	Ẋ	Ẏ	Ẍ	Ÿ
s	deg	deg	mm	mm	mm/s	mm/s	mm/s²	mm/s²
0	0	0	-174.9	99.99	-377	-345.5	971.1	-2810.7
0.25	45	90	-205.9	-51.04	224.6	-718.45	3109.9	635.9
0.5	90	180	-93.5	-154.6	364.69	99.8	-4519.1	6032.9
0.75	135	270	-93.1	92.23	-72.6	493.98	-4455.1	-6855.2

Fig. 26: Theoretical evaluation result



gear_ratio_calculator.m | theo_eval.m

```
l1 = 55.9; l2 = 134.63; l3 = 100; l4 = 100; l7 = 158.1;
phi0 = 116.565*pi/180;
gamma = 139.765*pi/180;
syms t real
dphi(t) = 2*pi*t;
phi = phi0+dphi;
l = sqrt(l1^2+l4^2-2*l1*l4*cos(phi));
theta2 = acos((l^2+l2^2-l3^2)/(2*l*l2)) - asin(l1/l*sin(phi));

xG = l1*cos(phi) + l7*cos(theta2+gamma);
yG = l1*sin(phi) + l7*sin(theta2+gamma);

xGdot = diff(xG,t);
yGdot = diff(yG,t);

xGdotdot = diff(xGdot,t);
yGdotdot = diff(yGdot,t);

for i=0:0.25:0.75
    disp("For iteration")
    disp(i)

    disp(double(xG(i)))
    disp(double(yG(i)))

    disp(double(xGdot(i)))
    disp(double(yGdot(i)))

    disp(double(xGdotdot(i)))
    disp(double(yGdotdot(i)))
end
```

Fig. 27: MATLAB script used for calculating the analytical kinematics

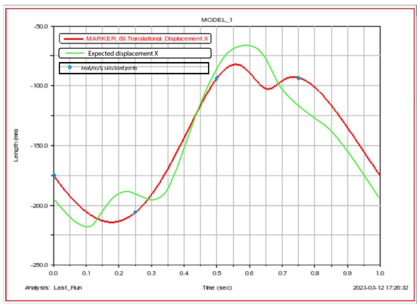


Fig. 28: Superimposed X displacement

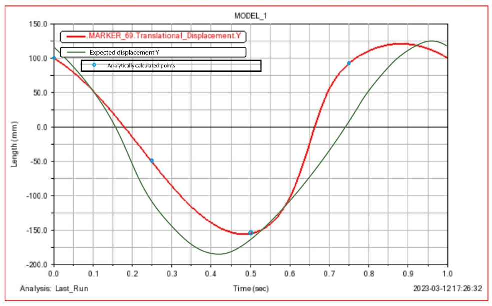


Fig. 29: Superimposed Y displacement

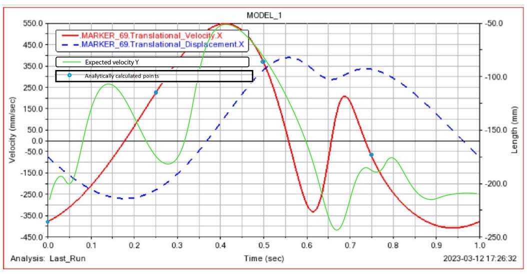


Fig. 30: Superimposed X vel

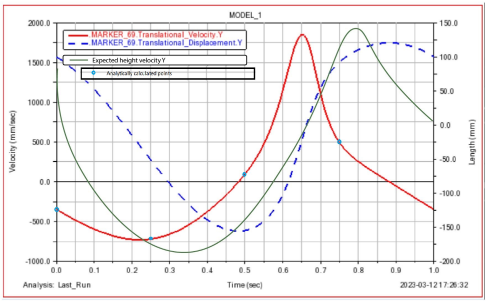


Fig. 31: Superimposed Y vel

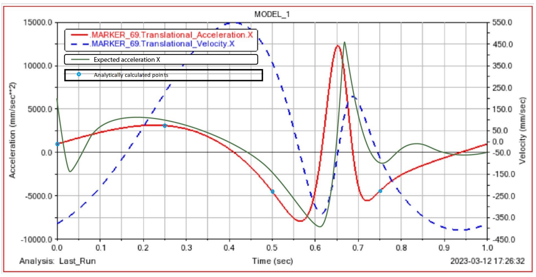


Fig. 32: Superimposed X acc

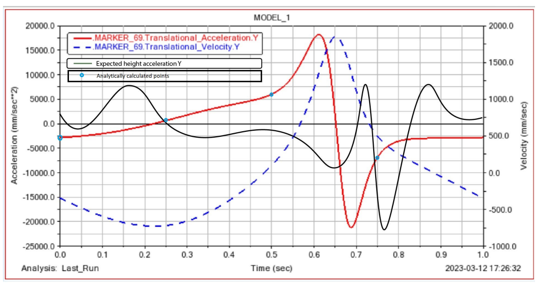


Fig. 33: Superimposed Y acc