International Journal of Latest Research in Engineering and Technology (IJLRET)
ISSN: 2454-5031
www.ijlret.com || Volume 02 - Issue 09 || September 2016 || PP. 30-42

Design, Analysis and Modelling of Pantograph Type Leg Mechanism for Humanoid Robot

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ABSTRACT : Walking machines are becoming more popular now a day because of their abilities of working in non-planned conditions. Because of that, these walking machines can reach nearly 75% land of the whole world which is not possible to reach by using wheeled machines. So by understanding its importance, in this research work a pantograph type walking mechanism has been designed, analysed and a prototype has been fabricated. The basic working principle of this walking mechanism is similar to that of pantograph mechanism. All its design part has been done in such a way that it can be used for designing an efficient and reliable humanoid robot whose control is easy because it is a 2-DOF walking mechanism. A standard walking trajectory has been developed which is perfect for efficient walking on normal surface and for arbitrary surface it is easy to generate modified trajectory as per requirement for that just a controlled input is required which can be generated by appropriate coordination of sensors, actuators and computational control. A scaled prototype of this pantograph type walking mechanism has been fabricated to understand different parameters like trajectory flow, friction, balancing etc. Also, a velocity and acceleration analysis of this prototype has been done. In this way the whole design, analysis and modelling of pantograph type leg mechanism for humanoid robot has been carried out.
KEYWORDS : Pantograph, Mechanism, Robot, Leg, Design.

I. INTRODUCTION

Machines are now becoming an essential part of human life. Day by day dependency of humans on machines is increasing which brings a requirement of development of machines. Apart from our traditional machines like Fan, TV etc. humans expecting more advanced machines in which machines can work with minimum supervision of human beings. From this point that is minimum supervision of human beings a concept of automation takes birth.

Automation is a technique or a method of operating or controlling a process by highly automatic means by using electronic devices like computer control. This automation is now a days expanding in industrial field. Industries are using automatic processing lines like welding line, painting line etc. Most of the industries are using wheeled devices for material handling and in their automatic processing lines. Because, these are simple to control and their efficiency is good. But because of certain limitations, that the wheeled robots have, it cannot be used everywhere and hence, it creates a necessity of design and development of wheeled robots.

Difference between wheeled and legged robots: -

1. Wheeled robots are easy to design and build while legged robots are comparatively difficult to design and build.
2. Wheel based robots require simple mechanics and computation to maintain equilibrium, orientation, efficiency and speed while Leg robots require complex mechanics and computation to maintain equilibrium, orientation, efficiency and speed.
3. Building a wheeled robot is easy compared to leg robots.
4. Wheeled robots travel faster than leg robots.
5. Legged robots must have a system to develop an appropriate Gait Cycle so that it can move in aspecific manner.
6. Dynamic stability of wheeled robots is very good but that of legged robots is poor.

Advantages of wheeled robots over legged robots: -

1. Surface conditions doesn’t affect performance.
2. Legged robots can jump or step over obstacles whereas wheels need to somehow travel over it.
3. Legged robots can avoid abnormal road conditions which may not possible by a wheeled robot.

4. Once it is moved from our smooth roads into rough, sandy, rocky steep and abnormal terrain, excellent invention of wheels turn out absolutely useless.
5. Importantly it is an attempt to replace human beings to similar machines/robots for avoiding human loss caused due to unavoidable reasons.
6. Lastly, an excitement of replicating a human or an animal and try to challenge nature.

Requirements of effective leg mechanism: -

1. Mechanism must be statically and dynamically stable.
2. DOF (Degree of Freedom) are such that it fulfils functional requirements and requires minimum actuators for its working.
3. Control of mechanism must be easy and perfect.
4. It must have to follow specified path only in each cycle.
5. It must consume minimum power for its actuation.
6. Require minimum maintenance, noise free operation and have capacity to tolerate any unavoidable effects like unbalanced force, unbalanced torque, shocks.
7. If a walking mechanism satisfy all above requirements, then it can be used for designing an effective walking machine.

Pantograph Mechanism: -

A pantograph is an assemblage of mechanical links connected to each other like a parallelogram, so that positional movement of one point is duplicated in other point but at different scale. Generally, at scale greater than unity. Based on that it is used in several machines. It is an example of four bar kinematic chain. It consists of a four links joined in such a way to form a parallelogram ABCD as shown in Fig. 1 in which AB=CD and AD=BC. In this EHGF always remains in straight line. Pantograph consists of four turning pair.

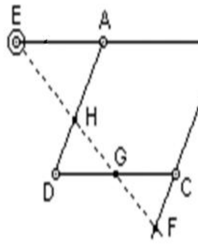

Fig. 1 Working of Pantograph Mechanism.

Basic way to understand working of pantograph mechanism as when F move line FE will always pass through H and G. This theory can be proved by using similar triangles. If it is so then it is clear that movements of F, G, and H are proportional to their distance from point E. If F moves to new position F' and H moves to new position H' then FF' and HH' are parallel to each other and are in ratio of EF to EH. In fact, this ratio is also equal to EA and EB.

II. DESIGN OF LEG MECHANISM

Trajectory planning is an important aspect of walking leg mechanism design because all objectives that have fixed are achievable only if mechanism functions smoothly and accurately as per planned way and for that reason trajectory planning is important.

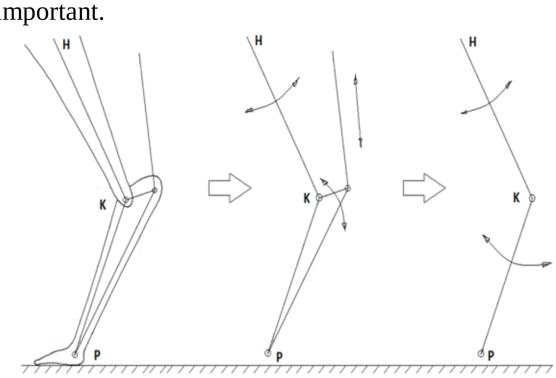

Fig. 2 Line Diagram of Controlling Mechanism.

Coordinates of control point: -

Coordinates of control point are calculated by resolving link lengths along both in X- axis and in Y-axis direction and adding them numerically to understand it a line diagram is shown in Fig.2. For that all angles and lengths, must be known so it become easy to find out coordinates of control point.
For calculation of resolving components resolve lengths along X- axis and along Y- axis sine and cosine functions are used for resolving them in respective axis direction.

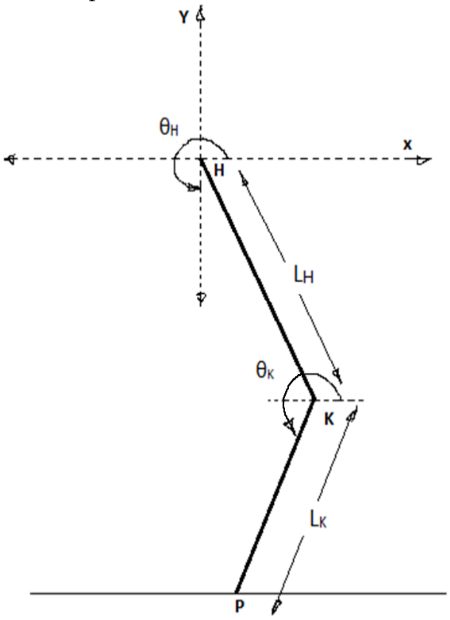

Fig. 3 Coordinates of Control Point P.

Nomenclature,

θ_H – Angle at hip joint
θ_K – Angle at knee joint
L_H – Length between hip joint and knee joint
L_K – Length between knee joint and ankle joint

Coordinates of control point P at zeroth position or initial position can find out from Fig. 3,

$$X_{p0} = L_H \cos(\theta_{H0}) + L_K \cos(\theta_{K0}) \ \ldots\ldots\ldots \ (1)$$

$$Y_{p0} = L_H \sin(\theta_{H0}) + L_K \sin(\theta_{K0}) \ \ldots\ldots\ldots\ldots \ (2)$$

Positions traced by the control point P during its one complete cycle are shown in Fig.4.

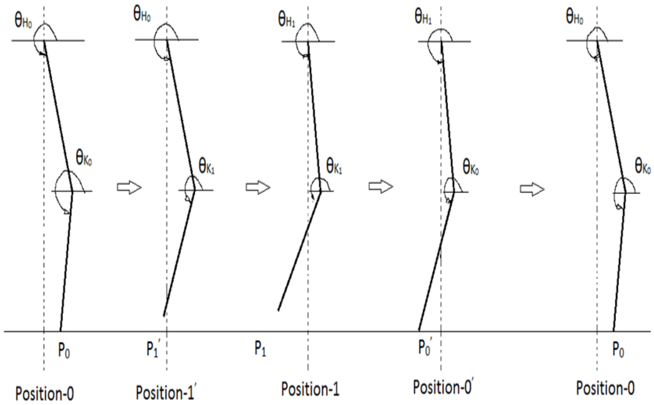

Fig. 4 Sequence of positions during one complete cycle.

Mechanism has to move in specific way to follow these positions like firstly it has to lift leg by some height to avoid ground contact during its movement.

It is must to rotate L_K link by θ_H angle to lift point P by a height of H as shown in Fig. 5. So θ_{K0} changes to θ_{K1} where,

$$\theta_{K1} = \theta_{K0} - \theta_H$$

θ_H is calculated by using following equations,

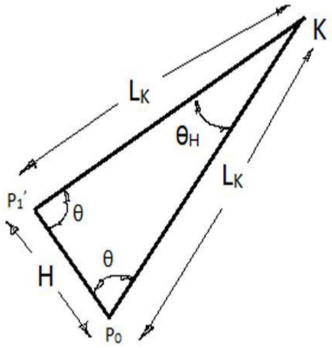

Fig. 5 Angular movement required to lift a point.

$$\theta_H + 2\,\theta = 180^0$$

$$2\,\theta = 180 - \theta_H$$

$$\theta = 90^0 - \frac{\theta H}{2}$$

By sine rule,

$$\frac{H}{Sin\theta H} = \frac{Lk}{Sin\theta}$$

$$\frac{H}{Sin\theta H} = \frac{Lk}{Sin(90 - \frac{\theta H}{2})}$$

$$Sin(90 - \frac{\theta H}{2}) = \text{Cos}\,(\frac{\theta H}{2})$$

$$\frac{H}{Sin\theta H} = \frac{Lk}{Cos\,(\frac{\theta H}{2})}$$

$$\frac{H}{Lk} = 2 \bullet Sin\left(\frac{\theta H}{2}\right)$$

$$Sin\left(\frac{\theta H}{2}\right) = \frac{H}{2\,Lk}$$

$$\frac{\theta H}{2} = \text{Sin}^{-1}(\frac{H}{2\,Lk})$$

$$\theta_H = 2\ \text{Sin}^{-1}(\frac{H}{2\,Lk})$$

From this angle θ_H find out θ_{K1} by using following equation,

$$\theta_{K1} = \theta_{K0} - \theta_H$$

So the new position of point P at height H is $P_{1'}$ and its coordinates are given as follows,

$$X_{p1'} = L_H \text{ Cos } (\theta_{H0}) + L_K \text{ Cos } (\theta_{K1})$$

$$Y_{p1'} = L_H \text{ Sin } (\theta_{H0}) + L_K \text{ Sin } (\theta_{K1})$$

When leg rotated through angle θ_A through hip,

$$\theta_{H1} = \theta_{H0} - \theta_A$$

New coordinates of point P at point P_1 are,

$$Xp1 = L_H \text{ Cos } (\theta_{H1}) + L_K \text{ Cos } (\theta_{K1})$$

$$Yp1 = L_H \text{ Sin } (\theta_{H1}) + L_K \text{ Sin } (\theta_{K1})$$

When it is necessary to step down the feet, now θ_{K1} changes back to θ_{K0} position.
So the new position $P_{0'}$ coordinates are,

$$X_{p0'} = L_H \text{ Cos } (\theta_{H1}) + L_K \text{ Cos } (\theta_{K0})$$

$$Y_{p0'} = L_H \text{ Sin } (\theta_{H1}) + L_K \text{ Sin } (\theta_{K0})$$

At the time when foot has to come back to starting position θ_{H1} must changes to its original position θ_{H0}.
Foot point comes back to starting position whose coordinates are,

$$X_{p0} = L_H \text{ Cos } (\theta_{H0}) + L_K \text{ Cos } (\theta_{K0})$$
$$Y_{p0} = L_H \text{ Sin } (\theta_{H0}) + L_K \text{ Sin } (\theta_{K0})$$

Design of Mechanism considering dimensions of Human Being: -
Standard dimensions of human beings according to ISO/TR 7250-2:2010 standard are,

$$L_H = \text{Length between hip joint and knee joint} = 50 \text{ cm}$$
$$L_k = \text{Length between knee joint and ankle joint} = 40 \text{ cm}$$

This mechanism is designed mainly for maximum stability for that reason it is necessary to take a small step size of 20 cm. For that move control point 10 cm front and 10 cm back of centre line.
At P_0 position,

$$X_{p0} = + 10 \text{ cm}$$
$$Y_{p0} = - 80 \text{ cm}$$

But,

$$X_{p0} = L_H \text{ Cos } (\theta_{H0}) + L_K \text{ Cos } (\theta_{K0})$$
$$Y_{p0} = L_H \text{ Sin } (\theta_{H0}) + L_K \text{ Sin } (\theta_{K0})$$

By solving these two equations you will get,

$$\theta_{K0} = 247.38^0$$

and

$$\theta_{H0} = 300.51^0$$

Hence at P_0 position,

$$\theta_{H0} = 300.51^0, \theta_{K0} = 247.38^0,$$
$$X_{p0} = 9.99 \text{ cm}, Y_{p0} = - 80.00 \text{ cm}$$

Amount of height required at control point to avoid ground contact at the time of motion: -
This value is calculated from the formula derived earlier.

$$\theta_{K1} = 230.120$$

New position after lifting is,

$$X_{p1'} = - 0.25 \text{ cm}$$
$$Y_{p1'} = - 73.77 \text{ cm}$$

After that turn leg about hip for its forward motion.
Amount by which leg must be rotated through hip,

$$\theta_{Hip} = \theta_{H0} – \theta_{H1}$$
$$\theta_{Hip} = 300.5102169 – 286.2602047$$
$$\theta_{Hip} = 14.2500122^0$$

New position of point is calculated as follows,

$$X_{p1} = L_H \text{ Cos } (\theta_{H1}) + L_K \text{ Cos } (\theta_{K1})$$
$$Y_{p1} = L_H \text{ Sin } (\theta_{H1}) + L_K \text{ Sin } (\theta_{K1})$$

So the third position is,

$$X_{p1} = - 11.64 \text{ cm}$$
$$Y_{p1} = - 78.69 \text{ cm}$$

Similarly, at position $P_{0'}$

$$X_{p0'} = - 10 \text{ cm}$$
$$Y_{p0'} = - 80 \text{ cm}$$

But,

$$X_{p0'} = L_H \text{ Cos } (\theta_{H1}) + L_K \text{ Cos } (\theta_{K0})$$
$$Y_{p0'} = L_H \text{ Sin } (\theta_{H1}) + L_K \text{ Sin } (\theta_{K0})$$

By solving these two equations,

$$\theta_{K0} = 233.13^0$$

and

$$\theta_{H1} = 286.26^0$$

Hence at $P_{0'}$ position,

$$\theta_{H1} = 286.2602047^0, \theta_{K0} = 233.1301024^0,$$
$$X_{p0'} = -9.99 \text{ cm}, Y_{p0'} = - 80.00 \text{ cm}$$

Trajectory of motion that the control point follow is,

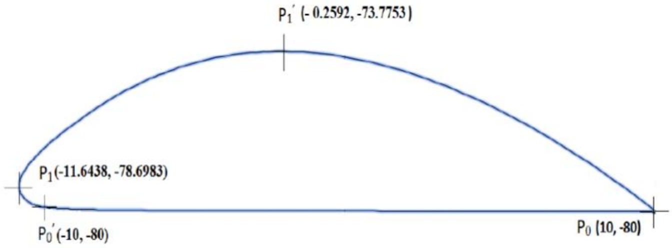

Fig. 6 Trajectory of Foot Point.

All these positions are,

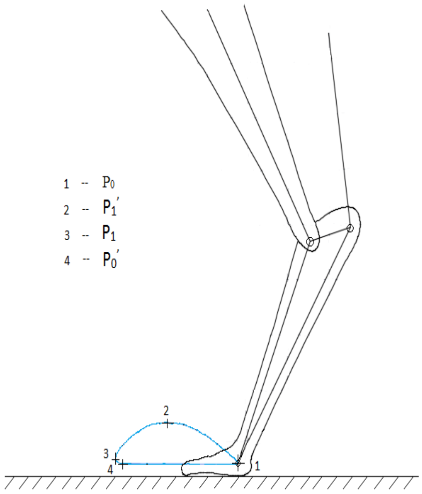

Fig. 7 All positions are shown in one cycle.

III. MODELING OF LEG MECHANISM

First of all, a 3D- Model of walking leg mechanism has been made by using Auto-Cad shown in Fig. 8 and Fig.9 for that required dimensions are taken from Design of Walking Mechanism discussed earlier in which most important parameters are calculated for controlling mechanism. Supporting dimensions are calculated at time of prototype fabrication to satisfy functional requirements.

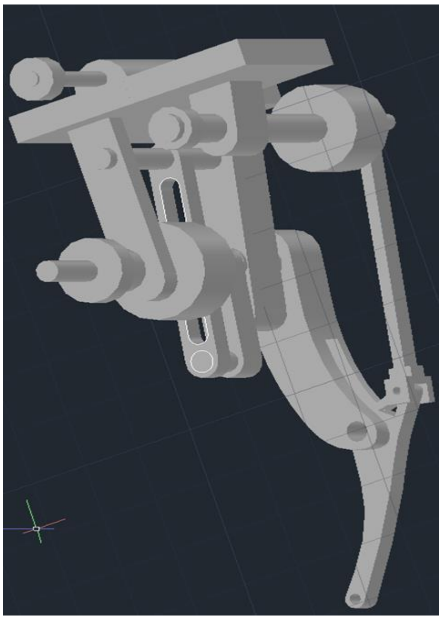

Fig. 8 3D-Model of One Complete Leg.

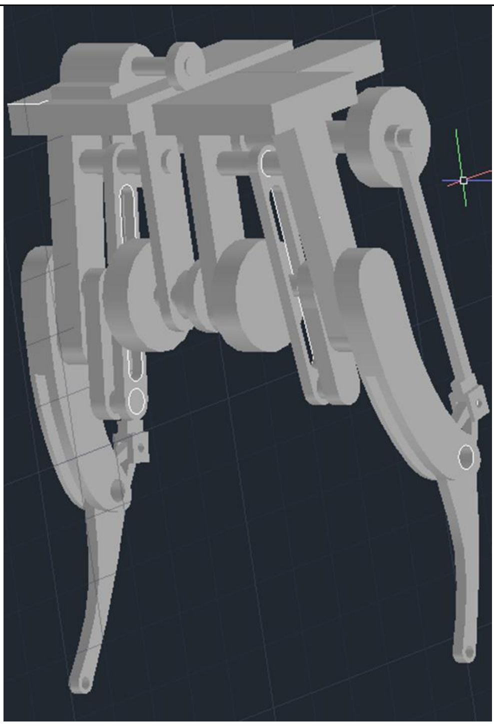

Fig. 9 3D-Model of Complete Leg Pair.

Different parts of Leg Mechanism: -

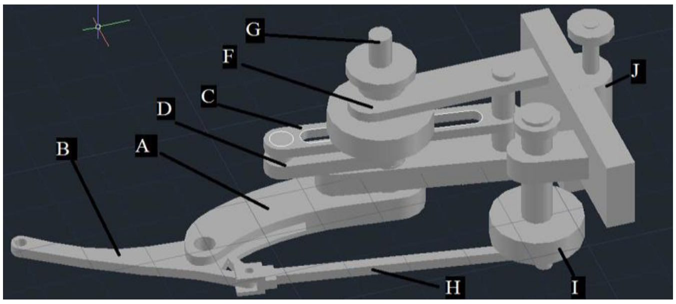

Fig. 10 Different Parts of 3D-Model of One Complete Leg.

Table 1. Different parts of Leg Mechanism: -

Sr. No.	Part Code	Description of Part
1	A	Motion transmitter from input to main foot
2	B	Main foot supporter or controller
3	C	Slotted lever for converting motion
4	D	Transmit motion from slotted to sub supporter A
5	E	Motion converter from rotary to oscillatory
6	F	Base supporters
7	G	Shafts
8	H	Lever for lifting leg
9	I	Eccentric Disc
10	J	Motor

Complete assembled prototype of one leg mechanism: -

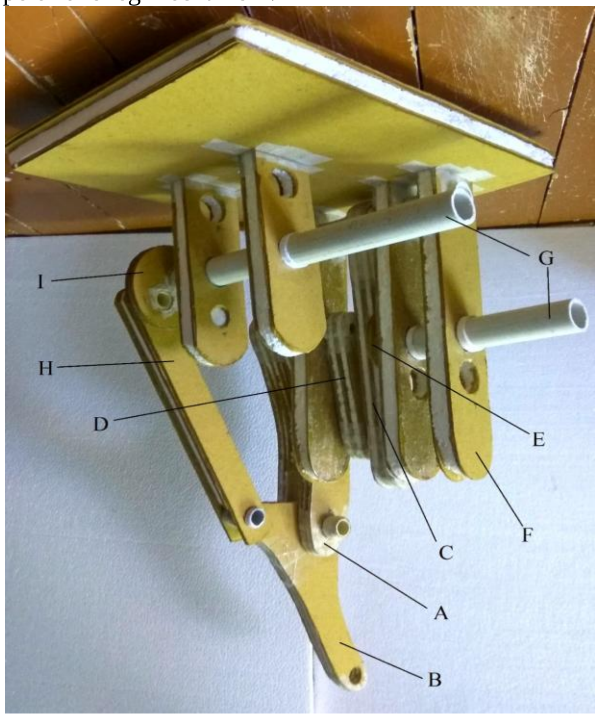

Fig. 11 Pantograph Type Leg Mechanism.

IV. WORKING AND BALANCING OF LEG MECHANISM

In one complete cycle of walking i.e. in one step of walking end point of part B follows trajectory shown before in which it travels through four main positions as shown in trajectory fig.6.2 these points are P_0 – $P_{1'}$ – P_1 – $P_{0'}$ and comes back to P0 position. This whole movement will be covered in four steps that motion transmission way is elaborated.

In main motion input is provided to Link-E by using shaft G this Link-E converts this input rotary motion into oscillatory motion because of cam like arrangement between Link-E and Link-C. All Links are listed in Table 1 and shown in Fig. 10 and Fig. 11. Now, this oscillatory motion is transferred to Link-A by using Link-D. Link-D and Link- Link-A are rigidly connected to each other. In this way main functional input is provided to foot point situated at end of Link-B.

Now, second supporting input which is responsible for lifting leg is provided to Link-I by using input shaft G. This Link-I converts rotary motion into oscillatory motion and this oscillatory motion is provided to Link-B by using Link-H. In this way the supporting input will be provided to mechanism.

Step – 1: -

In this step a rotary input is given to Link-I through input shaft in such a that it will bring it to certain height so that there is no more contact between ground and foot. At that just before other leg comes in contact with ground so that leg balances its weight.

In this step foot point travels from P_0 to $P_{1'}$ now it is free to travel ahead and then second step will be executed.

Step – 2: -

In this step two input motions are provided to both the inputs. One is for Link-I and other is for Link-E such that foot point travels from $P_{1'}$ to P_1. Up to this leg is in air there is no direct contact between leg and ground.

Step – 3: -

In this step as like as step-1 foot of mechanism brings in contact with ground by providing input to Link–I.

Step – 4: -

This step is similar to that of step-2 in which leg comes to its original position by simultaneous movement of Link-I and Link-E.

Same cycle will be executed by the other leg but in such a way that when left leg comes in contact with the ground right leg lose its contact with ground and vice versa in this way complete walking cycle will be completed and complete system travels some distance.

V. VELOCITY AND ACCELERATION ANALYSIS

Velocity and acceleration analysis is analysis by which it is easy to judge performance of mechanism. In this mechanism different linkages are attached to each other in 3D space which makes this mechanism complicated for analysis to make this analysis easy it is necessary to divide the whole mechanism into two parts. This division also makes easy for understanding this velocity and acceleration analysis.

Velocity Analysis: -

Input is given to Part-E through shaft G. Consider that the mechanism is at position such that Link-C is at extremely low position. Let us suppose input rotational velocity is ω_1 rad/sec. Then same rotational velocity is transferred to Link-A at this position because tangential velocity is perpendicular to both links i.e. Link-C and Link-D.

So tangential velocity at lower support of Link-A is,

$$V_1 = R_1 \times \omega_1$$
$$V_1 = 25 \times \omega_1$$
$$V_1 = 25\ \omega_1$$

Similarly, suppose ω_2 input is provided to Link-I by using another input Shaft-G. This input is responsible for lifting the leg up to certain height to avoid ground contact. Suppose link is at extremely forward position as shown in fig.11 at that position velocity is tangentially transferred to Link-B from Link-I.
So the input velocity received at Link-B from input side is,

$$V_2 = R_2 \times \omega_2$$
$$V_2 = 5 \times \omega_2$$
$$V_2 = 5\ \omega_2$$

Both these components act on the main foot controlling Link-B as shown in Fig. 12. So it is necessary to find out their resultant to understand their combined effect. Their resultant force is responsible for lifting the leg and simultaneously it moves leg in forward direction for its movement and this movement is our desired effect of all inputs.

Velocity component V_2 has to resolve into two components i.e. radial component V_{2R} passing through origin of velocity vector V_1 and a tangential vector V_{2T}.

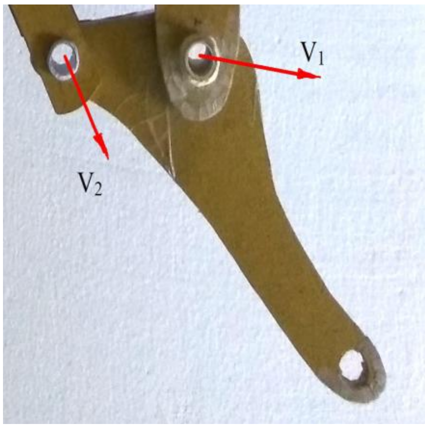

Fig. 12 Velocity Components of Two Different Inputs.

Resultant velocity is calculated by using vector addition.
Velocity component V_{2T} is responsible for lifting the foot up to certain height to avoid ground contact.
In normal walking humans will walk at a speed of 75 steps per minute. Which means this mechanism also has to complete its 75 complete foot step cycles in one minute for that a 75 rpm input is required.
So, take N_1 = 75 rpm.

$$\omega_1 = \frac{2\pi n}{60}$$

$$\omega_1 = \frac{2\pi 75}{60}$$

$$\omega_1 = 7.81 \text{ rad/sec}$$

For foot lifting same amount of rotational speed is required. Because number of foot lifting cycles are equal to number of walking step cycles.
Hence, ω_2 = 7.81 rad/sec.
So velocities are,

$$V_1 = 25\ \omega_1$$

$$V_1 = 25 \times 7.81$$

$$V_1 = 195.25 \text{ cm/s}$$

And

$$V_2 = R_2 \times \omega_2$$

$$V_2 = 5\ \omega_2$$

$$V_2 = 5 \times 7.81$$

$$V_2 = 39.05 \text{ cm/s}$$

To find combined effect of these two velocities it is necessary to resolve V_2 component into two radial component and tangential component.
Angle between V_2 and radial component is 65^0.So; two different components are calculated as follows using following equations.

$$V_{2R} = V_2 \text{ Cos}65$$

$$V_{2R} = 39.05 \text{ Cos}65$$

$$V_{2R} = 16.40 \text{ cm/s}$$

And tangential component is,

$$V_{2T} = V_2 \text{ Sin}65$$

$$V_{2T} = 39.05 \text{ Sin}65$$

$$V_{2T} = 35.14 \text{ cm/s}$$

This V_{2T} i.e. 35.14 cm/s is the velocity which is responsible for lifting the leg to certain height to avoid ground contact.
Angle between V_1 and V_{2R} is 25^0.

$$R_V = \sqrt{V1^2 + V2R^2 + 2\ V1\ V2R\ Cos25}$$

$$R_V = \sqrt{195.25^2 + 16.4^2 + 2\ \times 195.25 \times\ 16.4\ Cos25}$$

$$R_V = 210.22 \text{ cm/s}$$

This R_1 i.e. 210.22 cm/s is the velocity which is responsible for rotating the leg about hip joint to advance step in forward direction at this position.

Acceleration Analysis: -

Acceleration analysis of a mechanism is important because it is the parameter which is responsible for production of inertial forces. It is always desired that the unwanted acceleration must be as minimum as possible. As shown in fig.11 at extremely low position of Link-E, Link-C and Link-D are tangentially connected to each other. So, whatever input angular velocity and angular acceleration provided to Link-E is directly transferred to Link-A through Link-C and Link-D.

Hence input for Link-A and Link-E is same at extremely low position of Link-E. So, at lowest support of Link-A acting acceleration is resultant of centripetal acceleration and tangential acceleration.

Suppose, Link-E is rotating in anticlockwise direction with angular velocity ω_1 and angular acceleration α_1 in anticlockwise direction.

Centripetal acceleration,

$$a_{CP1} = R_1 \times \omega_1^2$$

$$a_{CP1} = 25 \times \omega_1^2$$

$$a_{CP1} = 25\ \omega_1^2$$

$$a_{CP1} = 25 \times 7.81^2$$

$$a_{CP1} = 1524.9\ cm/s^2$$

this acceleration is acting towards the rotating input center of Link-A.

suppose $\alpha_1 = \alpha_2 = 500\ rad/s^2$

Tangential acceleration,

$$a_{T1} = R_1 \times 500$$

$$a_{T1} = 25 \times 500$$

$$a_{T1} = 12500\ cm/s^2$$

this component of acceleration act in tangential direction in anticlockwise direction to the Link-A.

At the bottom portion of Link-H only tangential component acceleration of Link-I will be act.

Tangential acceleration acting on Link-B through Link-H is,

$$a_{T2} = R_2 \times \alpha_2$$

$$a_{T2} = 5 \times 500$$

$$a_{T2} = 2500\ cm/s^2$$

Angle between a_{T2} and radial component is 65^0.So; two different components are calculated as follows using following equations.

$$a_{T2R} = a_{T2}\ Cos65$$

$$a_{T2R} = 2500\ Cos65$$

$$a_{T2R} = 1056.54\ cm/s^2$$

And tangential component is,

$$a_{T2T} = a_{T2}\ Sin65$$

$$a_{T2T} = 2500\ Sin65$$

$$a_{T2T} = 2265.76\ cm/s^2$$

Angle between a_{T1} and a_{T2R} is 25^0.

$$R_A = \sqrt{aT1^2 + V2R^2 + 2\ aT1\ aT2R\ Cos25}$$

$$R_A = \sqrt{1056.54^2 + 12500^2 + 2 \times 1056.54 \times 12500\ Cos25}$$

$$R_A = 13464\ cm/s^2$$

That much amount of acceleration is going to act on link in rotating direction.

VI. RESULTS

Main objective of this work is to design a walking leg mechanism which can produce walking trajectory just like human beings. So the produced trajectory is,

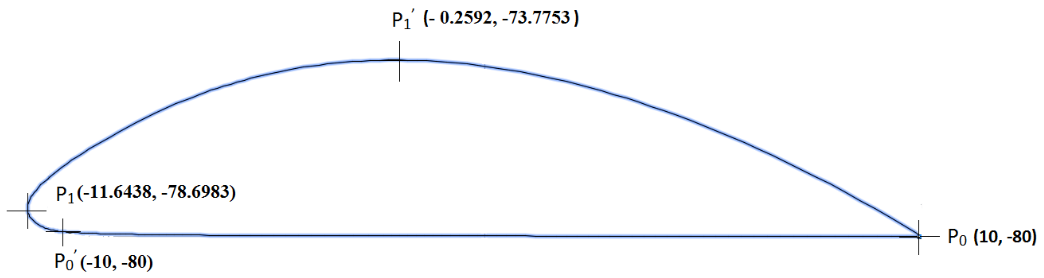

Fig.13 Trajectory of Foot Point.

It satisfies the walking requirements and fulfils the criteria of effective leg mechanism hence our main objective is achieved.

Similarly, as explained in design of walking mechanism that two main links are controlling the foot point so by changing their orientations it is possible to change trajectory as per your requirement depending on type of application.

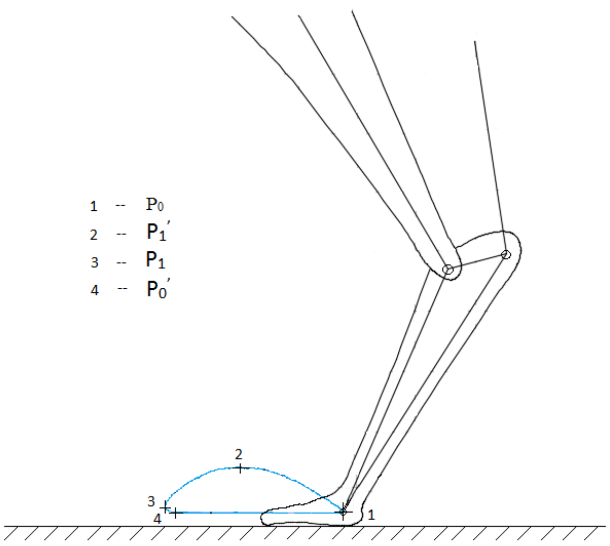

Fig.14 Two Main Controlling links of Mechanism.

Controlling links are shown in fig.14 also because of its ability of changing the trajectory as per requirement this mechanism can be effectively used to walk over stairs.

Table 2. Foot Point Trajectory: -

Sr. No.	Point	(X, Y) Position in cm	Function
1	P_0	(9.99, - 80.00)	To support at initial position
2	P_1'	(-0.25, - 73.77)	Lifting to avoid ground contact during movement
3	P_1	(- 11.64, - 78.69)	Lifting to avoid ground contact during movement
4	P_0'	(-9.99, - 80.00)	To support at rear position
5	P_0	(9.99, - 80.00)	To support at initial position

As shown in table-2 the generated trajectory satisfies the requirement for effective walking.

As it is a symmetric mechanism shown in above and all accessories are in between the bounded areas of two legs hence gravity always lies in between the bounded area of two legs which makes this mechanism more stable.

VII. CONCLUSION

Primary objective of this research work is designing a walking mechanism which is simple in manufacturing, assembly and control is achieved, for that a prototype model is fabricated and based on its functioning it is shown that this pantograph type leg mechanism can be effectively used for walking of humanoid robot. The trajectory that this mechanism is producing when a controlled input is provided is suitable for balanced walking.

VIII. Acknowledgements

I express my deepest sense of regards and gratitude to my guide **Dr. Vilas Warudkar**, Assistant Professor, Department of Mechanical Engineering, M.A.N.I.T.I also gratefully acknowledge all inspiring effort of my **family and friends** who constantly encouraged me to maintain the level of enthusiasm for completing this dissertation work at various stages.

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