DESIGN AND FABRICATION OF BIO-INSPIRED ROBOT USING PEAUCELLIER-LIPKIN LEG LINKAGE

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ABSTRACT

The main aim of this project is presents a new single degree-of-freedom crank driven walking leg mechanism which is used for walking machines. The mechanism is planar Peaucellier- Lipkin type having eight links. Using this type mechanism a walking robot with eigth legs is designed and fabricated. Initially a walking leg mechanism is prepared. Its kinematics and synthesis analysis is conducted to achive desires stride length using "mechanical linkage analysis software. Further the same mechanism are produced with eight numbers. Also a frame is fabricated. These mechanisms and frame are assembled to produce octopod bio-inspired robot by adding necessary electronic devices. Legs and frame are fabricated with Aluminum material due to its is light weight.

Furthermore kinematic analysis of the bio-inspired robot is carried out. Finally the robot is made to walk on surface.

1. INTRODUCTION

Many animals in nature have adopted legs for various environmental conditions. Centipedes, spiders, cockroaches, cats, camels, kangaroos, and human are among those, either with different number of legs or with different kind of walking. It is understandable that people turned their attention to those walking animals, after it was recognized that the human invented wheeled and tracked systems did not satisfy all the needs. In this sense, legged systems have a peculiarity of imitating the nature.

This imitation is obvious in structural similarity between legged robots and imitated animals; however, for today the imitation is not limited to structural design. Today researchers are trying to understand the underlying biological principles of walking in animals, namely the operational and control structures.In biological sciences and robotics applications the most important item is the plan and coordination of leg movements. Movement is a fundamental distinguishing feature of animal life. The locomotion over a surface by means of limbs or legs can be defined as walking whatever are the number of limbs or legs that are used different ways of walking have been achieved by the evolutionary process in nature.

The plan of walking, namely the "gait pattern", determines the sequence of stepping of legs with their stance and swing durations in each step. Mahajansteal(1997) gives the following definition for gait: "The gait of an articulated living creature, or a walking machine, is the corporate motion of the legs, which can be defined as the time and location of the placing and lifting of each foot, coordinated with the motion of the body, in order to move the body from one place to another." Animal gaits can be divided into two main groups as statically stable and dynamically stable.

It introduces more flexibility and terrain adaptability at the cost of low speed and increased control complexity. In order to develop dynamic model and control algorithm of legged robots, it is important to have good models describing the kinematic behaviour of the complex multi-legged robotic mechanism as walking machines are increasingly gaining importance in space for planetary exploration, where the terrain is rugged thus reducing the expensive and dangerous extra vehicular Activities by Astronauts. Walking machines find wide range of applications like in military logistic support where there are no highways

Legged locomotion is a proper solution for movements on loose-rough-uneven terrains. This advantage of legged locomotion is mostly due to the fact that legged systems use isolated footholds. Wheeled and tracked systems follow the surface in a continuous manner; therefore, their performance is limited by the worst parts on the terrain. A legged system, on the other hand, can choose the best places for foot placement. These footholds are isolated from the remaining parts; hence the performance of the legged system is limited by the best footholds. Besides using isolated footholds, the legged system can provide active suspension, which does not exist in wheeled or tracked systems. This means that the system can have control on the force distribution through the foothold points. In this way an efficient utilization of the footholds provides further improvement of the vehicle-ground interaction. A legged system is well adaptive to uneven terrains, namely the legs can be arranged (lengthened and shortened according to the level changes, and they can jump over obstacles or holes. Therefore, the body can be moved in a desired orientation, The legged locomotion is disadvantageous considering the system control and energy consumption. Legged mechanisms have complicated kinematics and dynamics, and a lot of actuators have to be controlled in continuous coordination; therefore, control of legged systems is more difficult in comparison to wheeled and tracked systems. Since they are comparatively novel development, there are no well-established technologies for legged systems

This Project work is concerned with a mechanism that lent itself for a mechanical walking machine, describing the new mechanism. Qualitatively and mathematically. The method of solving both the kinematics of the various links in the linkage and also provided a method of investigating the forces within the mechanism as it moves.

There has been much research into walking as a means of locomotion. Many designs of machine using a variety of means of obtaining foot motion have been developed over the years. If a new class of mechanism is worth considering, it needs to be located in the context of the other solutions attempted. The advantages of a new method must be demonstrated not only in relation to alternative designs for walking machines, but also in relation to other forms of overland locomotion, especially wheels and tracks.

1.1 OBJECTIVE OF THE WORK

The primary goal of this thesis is to create a suitable theoretical frame work to justify the design choices for a new type of walking machine with the inspiration of a spider waking mechanism.

Further, another aim is to use this design opportunity to fabricate the eitht legged bio-inspired robot using the light weight material. The main parts like body and legs are made with aluminium.

1.2 Background

A walking machine that is able to walk like an animal should have a leg mechanism that produces a nearly straight stride path (propelling path). A continuously rotating actuation system that produces a closed ovoid-shaped foot path is required. Single DOF (degrees of freedom) leg mechanisms are simple and are suitable in some areas. Many such mechanisms were developed using four, six and eight links, they were straight-line mechanisms. Four link mechanisms such as Chebyshev, Grasshopper and Hoecken's and six link mechanisms that have either Watt's or Stephenson's topology has been developed. Klann's linkage uses Stephenson's topology. The other types of linkages with eight links have different methods of operation; they are based on Peaucellier–Lipkin mechanism type behavior. Theo Jansen's and Ghassaei's walking leg linkage is of this type. All the above-mentioned linkages make use of coupler curves and are modified by inversion and amplification

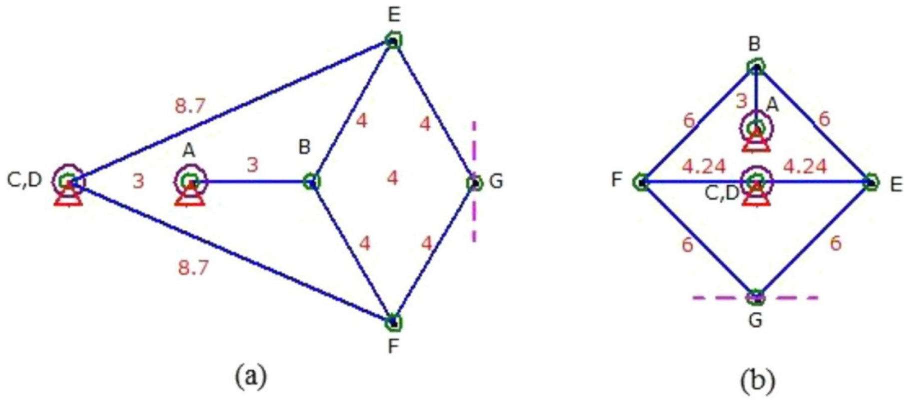


Figure 1. Peaucellier– Lipkin mechanism and its inversion

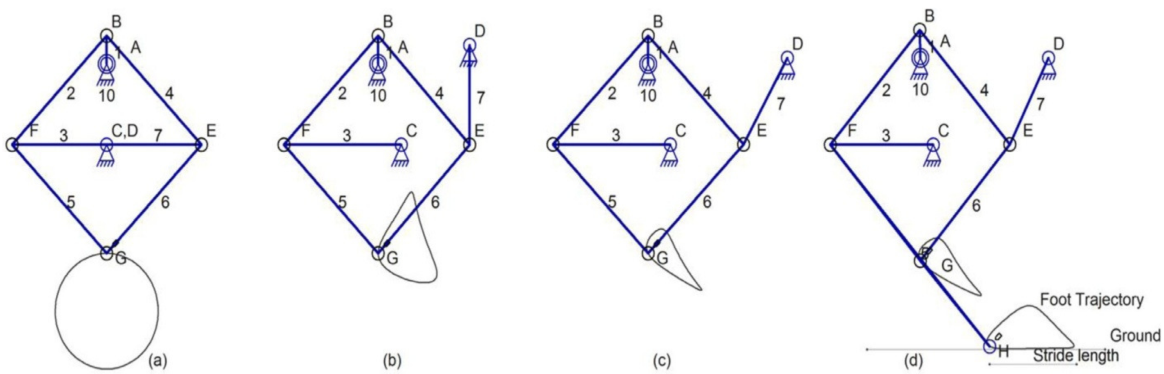


Figure 2. Development of leg mechanism

the Peaucellier-Lipkin linkage so that crank driving the linkage AB makes a complete rotation, and this will make the mech- anism to operate continuously and the second objective was to observe the possible shapes of trajectories by changing the geometrical configuration of the linkage, and the possible outcome was to trace a closed ovoid trajectory the part of which is a straight line

In order to make the crank to have a complete rotation, the length of the crank AB is reduced to 60% of its original value. Fig. 1(b) is redrawn by reducing the length of the crank which is shown in Fig. 2(a), the links and joints are labeled. In this configuration, the rotation of the crank (labeled as 1) results in point G tracing a circle. Modification of this mechanism is performed by separating link 7 from a common pivot at C and rotating the link 7 by 90o clockwise, another fixed pivot is created at D

2. LITERATURE REIVEW

The present chapter deals with the design, kinematics, gait plan, and fabrication of singledegree-of freedom robots.

2.4 Literature Summary

[1] Shivamanappa G. Desai,(2019) : this paper, a new walking leg mechanism is presented. The geometry and working are explained. Kinematic analysis and simulation is performed by MATLAB and Linkage 3.0. The results of kinematic analysis are used in optimization. The experimental model of both mechanism and walking machine is built and tested for its practical accuracy. The mechanisms analytical results are compared with simulation and also compared with foot trajectory traced by the fabricated model.

[2]T. Zielinska(2004) : The mechanical structure of the prototype must be very well assembled for effective self-locking. When this is the case, smaller torque in the hip is required and gear reduction can be decreased which increases walking speed. As the payload and speed are inversely proportional in relation to the gear reduction, differential gear has the advantage in torque when compared to the classic design (torque benefit depends on the quality of manufacturing).

[3] Amanda Ghassaei(2011) : 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. The linkage was simulated in Mathematica, and an analysis of the leg design, including an analysis of the foot path and center of mass is 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 center of mass movement during locomotion than the Theo Jansen mechanism, but its step height is about 33% less. A detailed description of the fabrication of a six-legged walker made primarily from PVC tubing is given, as well as suggestions for improvement and future work

[4] Sun-Wook Kim(2011) : In this research, a crab robot is implemented in H/W based on Jansen mechanism, and its kinematics is analyzed. The proposed biologically inspired robot is applicable to solve many engineered problems, since it is able to walk with maintaining its body still. In this paper, the twelve-bar linkage of a crab robot is analyzed kinematically

[5] V. Arakelian(2014) : In all likelihood, robotics will lead to a revolution in our lifestyle similar to internet or mobile phone. In this context, the design of walking systems is currently one of the most invested fields, which leads to the development of new products with large diversity. Among of these products may be well distinguished the multi degrees of freedom legged walking robots and the walking machines with legs having one or two degrees of freedom. Despite its long history, design of walking robots continue to develop and new solutions are constantly being reported. This paper provides an overview of walking robots

[6] Shunsuke Nansai1*, Mohan (2020) : This paper reported a design approach to using toe speed control towards achieving complex gaits with the Jansen linkage mechanism. It has been proven that the norm of the toe speed bears a proportionate relationship to the angular velocity of the driving link. Using this relationship as basis, we derived the angular trajectory that results in a constant toe speed in the robot platform. Numerical simulations were performed to demonstrate the efficacy and validity of the proposed approach. An application case demonstrating the use of the proposed approach has been presented that involves derivation of angular trajectory capable of speed control of the toe in horizontal direction.

[7]James P.M.(2019) : Quadruped robots which are gaining attention now days have to be further developed by giving the adaptive knowledge towards terrain locomotion and can be programmed with a better dynamic model for super dexterous capabilities the project vision is to develop a walking robot prototype with a novel design which has to be further developed. Future work includes implementing an adaptive controller for the robot to stabilize in uneven terrain locomotion has to been done to collect datas

[8] Adam Rushworth(2016) :The scope of this paper is to present a novel method of actuating the legs of a walking parallel kinematic machine tool (WalkingHex) such that the upper spherical joint passive joint can be actively driven while walking and remain a free, while performing machining operations. Different concepts for the number of Degrees of Freedom (DoF) and methods for actuating the chosen concept are presented, leading to a description of a three-wire actuated spherical joint arrangement. The inverse kinematics for the actuation mechanism is defined and a control methodology that accounts for the redundantly actuated nature of the mechanism is explored. It is demonstrated that a prototype of the system is capable of achieving a motion position accuracy within 5.64% RMS . Utilising the concept presented in this paper, it is possible to develop a walking robot that is capable of manoeuvring into location and performing precision machining or inspection operations

[9]Adam Rushworth(2015) :The scope of this paper is to present a novel gait methodology in order to obtain an efficient walking capability for an original walking free-leg hexapod structure (WalkingHex) of tri-radial symmetry. Torque in the upper (actuated) spherical joints and stability margin analyses are obtained based on a constraint-driven gait generator. Therefore, the kinematic information of foot pose and angular orientation of the platform are considered as important variables along with the effect that they can produce in different gait torque analysis is studied to determine the motor cycles. The torque requirements for each step of the gait so that the robotic structure yields a stable and achievable pose. In this way, the analysis of torque permits the selection of an optimal gait based on stability margin criteria. Consequently, a gait generating algorithm is proposed for different types of terrain such as flat, ramp or stepped surfaces

[10] Tai Ye(2023) : Alkaline phosphatase (ALP) as an important biomarker as well as an index for the pasteurization degree of dairy food. However, there is a dilemma between the sensitivity and time-cost of ALP determination based on nucleic acid amplification approach. Herein, an ultrasensitive and rapid detection method for the ALP assay was developed based on entropy-driven DNA machine. In our design, the ALP catalyzed dephosphorylation of detection probe, which inhibited the digestion effect of lambda exonuclease. The remaining probe as a linker to tether the walking strand proximity to the surface of track strand modified gold nanoparticle, activating entropy driven DNA machine. Accompany with walking strand moving, a large amount of assembled dye-labelled strand dissociated from gold nanoparticle with fluorescence recovery. More importantly, to further improve the walking efficiency, butanol was introduced to accelerated the signal amplification at interface, which short the incubation time from several hours to 5 min. Under the optimum condition, the change of fluorescence intensity was proportion to the concentration of ALP in the range from 0.05 U L^{-1} to 5 UL^{-1} with an ultralow limit of detection of 2.07×10^{-3} U L^{-1} was achieved, which is superior to other reported methods. Furthermore, the proposed method also successfully applied for the spiked milk sample assay with satisfactory recovery in the range of

98.83%–103.00%. This work proposed a new strategy for the application of entropy-driven DNA machine in the field of rapid and ultrasensitive detection

[11] Luquan Li(2019) : This paper presents a class of novel 3-DOF single-loop parallel leg mechanisms for walking robots. A synthesis approach for single-loop parallel leg mechanisms has been proposed. Based on screw theory and the virtual work principle, feasible limbs are synthesized. Two types of equivalent drive mechanisms are designed. Moreover, novel single-loop parallel leg mechanisms are constructed based on the constraint synthesis method and the principle of equivalent substitution

3. WALKING MECHANISM AND MACHINES

Although it seems that the earliest walking machines were manufactured in the 1960's, in fact small toys, automata, have been manufactured in Europe since the 18th century, including bipedal walkers that became the inspiration of modern passive dynamic bipeds, such as the Cornell Bipedetc.

Subsequent to this early period, research into walking machines has been extremely active. Machines have been constructed on many scales, from some the size of insects, to some the size of small trucks. There are many sites on the internet which have extensive lists of walking machines The number and creativity of different methods of inspiring from all animals do so easily is staggering. Many possible walking mechanisms, from enormous two footed drag line excavators, to twelve-legged steam powered experimental prototypes have been attempted.

3.1 Classification

The Walking machines are classified into groups according to the number of legs they have. Animals too are classified on this basis, like bipeds (humans and birds), quadrupeds (mammals and reptiles), hexapods (insects), octopods (arachnids) or polypods (caterpillars, centipedes and millipedes).

Figure 3. Bipeds in birds

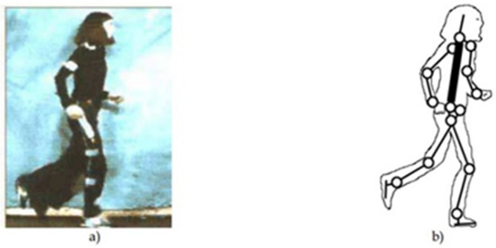


Figure 4. Bipeds in humans

The number of legs has a major impact on the physics of walking. To maintain a structure's position in a three-dimensional space requires three points of support. If a machine has fewer than three legs, it is said to be dynamically balancing. In other words, the walker must have some mechanism to vary the position of its centre of gravity in relation to its foot position, to prevent it falling over. Machines with three or more legs continuously in contact with the ground are said to be statically balanced, they may maintain their centre of gravity at any constant position, providing the vertical projection of this centroid is within the polygon constructed by connecting the foot points on the support plane. This polygon is known as the "support polygon" and would be triangular for a tripod or some form of quadrilateral for a quadrapeds.

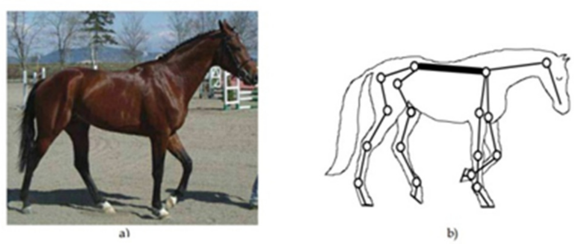


Figure 5. Bipeds in horse

3.2 BIPEDS

The Honda robot (Figure) and the Centaurob (Figure) are examples of this configuration. Bipeds are usually anthropomorphic. They attempt to mimic the human mode of locomotion. In most gaits that humans use to move, the foot of one leg is always on the ground. The other leg is lifted, and in the process of moving to a suitable position for the next foot fall.So,walking in humans equates to the balancing of a weight on a single column which is unconstrained in any dimension except its height. To maintain stability, the walking human or machine must ensure that their centre of gravity lies vertically above their footprint. As the legs and feet are usually arranged to lie side by side, the walker must move their centroid laterally by the size of the transverse pitch between the feet. This is the approach taken by humans and other natural bipeds, and also by the Honda robot.

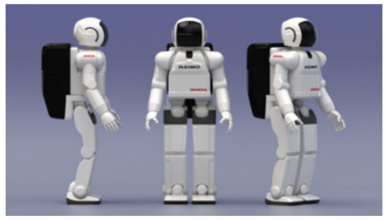


Figure 6. Prototypes of BiPeds

Another approach, as typified by the Centaurob, is to make the feet so large that their footprint is large enough to enclose a fixed centroid. Hence the annular shape of the feet on this machine. This is also the method used by walking drag lines. Some reduced lateral movement of the centroid may be required even with large feet.

Figure 7. Prototype of Bipes

Both of these approaches to maintaining stability have limitations. Active balancing requires a system to move the body, and sensors to detect position or imminent falling over and some type of response system to make corrections, in short, a control system. This control system makes any dynamically balanced walker complicated to design and implement. In large footed bipedal walkers, the size of the feet may limit where the machine can place them. Such a machine would also be relatively unstable, as the centroid location must be kept within a small range of positions, to ensure that it is always within the footprint. Any small changes in centroid position may make the walker topple over. This type of walker is only capable of walking on very flat surfaces, as any inclination or wobble in the foot can shift the centroid outside the footprint.

3.3 OCTAPEDS

Walkers with eight legs may maintain four legs on the ground at all times, and have four legs in the return stroke. The support polygon is a quadrilateral, with an area approximately twice that of the triangular support polygon of the hexapod with the same leg-base and track. This makes the vehicle much more capable of tolerating uneven walking surfaces, as the centroid position projection has a much greater locus of stable positions.

Figure 8. Prototype of OctaPeds

However, if the legs are non-compliant, the potential for a rocking condition can occur. This would occur on an uneven surface, where three legs find purchase, but rigidity of leg and frame prevents the fourth from reaching the surface. If the centroid changes position, due perhaps to leg movement, the walker body may shift weight onto the free leg, causing it to move ground ward, simultaneously lifting the leg which was on the ground before. The body would experience a rapid rocking motion, and perhaps some impact as the foot hits the ground. This could be dubbed the “restaurant table” effect.

3.4 MORE THAN EIGHT LEGS

Although walking machines have been designed with more than eight legs, these machines are rare. The extra complication of the extra legs does not usually create sufficient stability benefits to make the complication worthwhile.

Figure 9. Prototype with more than eight legs

4. Description and working of proposed walking leg mechanism

The proposed mechanism can be constructed in different geometric configurations. The first configuration is presented in Fig. 3, and depicts a side elevation, top view, front elevation and isometric view of walking leg mechanism. The foot trajectory of the mechanisms has two phases, viz.the stride phase and the lift phase.

4.1 Geometry of walking leg mechanism

The proposed walking leg mechanism is an eight link closed kinematic chain with 7 binary links (labeled 1–7) and a fixed link 8 as shown in Figs. 3 and 4. The mechanism is mounted on a supportive frame 8 having three fixed revolute joints A, C and D. Two crank rocker mechanisms (Grashof’s type) A–B–F–C and A–B–E–D having common driving crank 1 are placed on the frame such that the rockers of these mechanisms

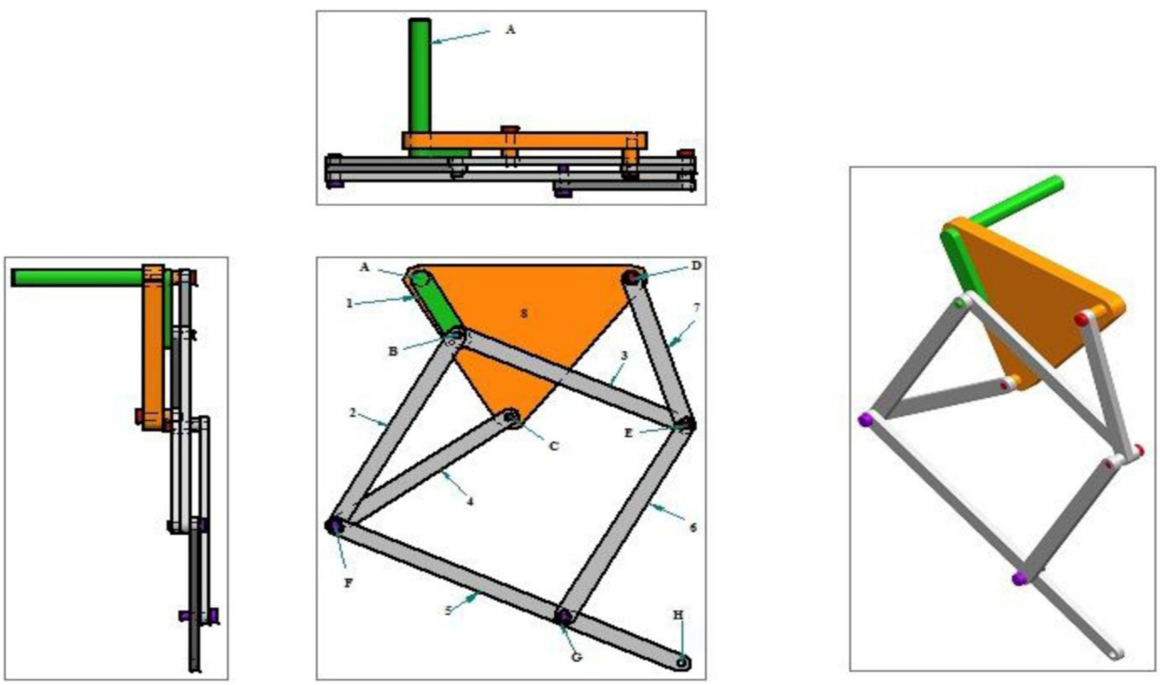


Figure 10. Geometry of the walking legmechanism

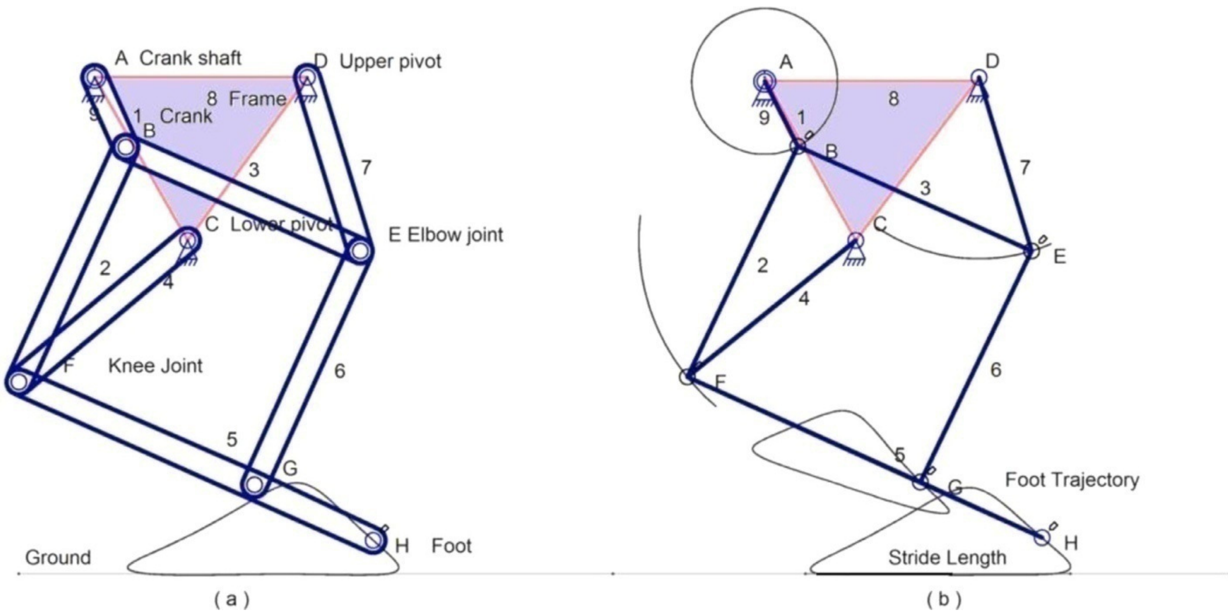


Figure 11. (a)Walking leg mechanism(b)Linediagram of the walking leg mechanism with the trajectory of each joint

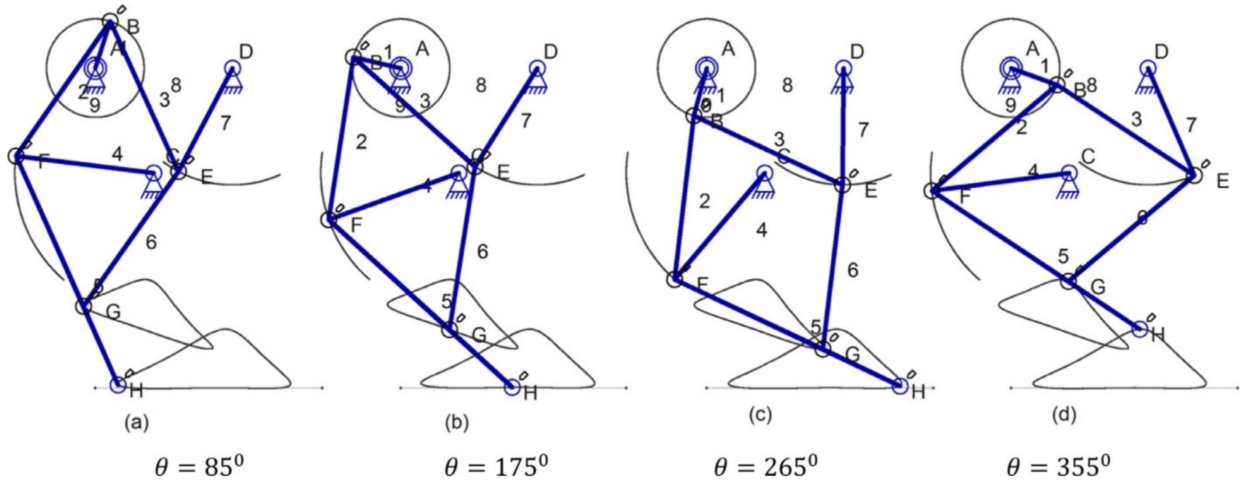


Figure 12. The leg position for different crank angle rotation.

The length between axial mounts of the various links of the walking mechanism and their respective spatial relationship has a direct bearing upon the orbital movements of the ground contact point or foot H. When it is desired to create a walking mechanism having a grounded stride measure as one unit, other links are measured by the ratio of the stride length. Using a stride length as one unit the other dimensions are calculated. the length of the crank 1 measures 0.254 units. The length of links 2, 3, part of 5 (length between joints F and G), and 6 is 0.853 units. The length of the joint G to the leg tip or foot H is measured 0.401 units. The length of the upper rocker arm 7 measures 0.60 units, and the length of the lower rocker arm 4 measures 0.7483units

4.2 Working of walking leg mechanism

The position of the walking mechanism for different crank rotations is shown in Fig. 5(a)–(d). The crank is rotated at 90° intervals and its starting position is 85o (measured counterclockwise from horizontal reference); this is when the leg begins its stride phase. At this position, the rocker arm 4 is inits extreme position and the rocker arm 7 is lagging by 65°. As the crank rotates counterclockwise (CCW) with constant angular velocity, the links connected will transfer the motion to the feet, and the feet H follows the approximate straight line towards the right, this will propel the vehicle in the opposite direction. When the crank has rotated 90o from the initial position Fig. 5(b) the second rocker arm 7 has reached its extreme position and rocker arm 4 is in the middle. When the crank rotates 180o from initial position Fig. 5(c), the lower rocker arm 4 has reached the extreme bottom position, and it is here the transition takes place and the foot H completes stride phase and begins to lift. The rotation of the crank to 270o from initial position Fig. 5(d), the second rocker arm 7 has reached its extreme right position, and rocker arm 4 is in the middle. As the two joints F and E move in the opposite direction, the diagonal of the parallelogram increases, and this increase will swing the leg 5 upward, thus lifting the feet Hup to the highest point.

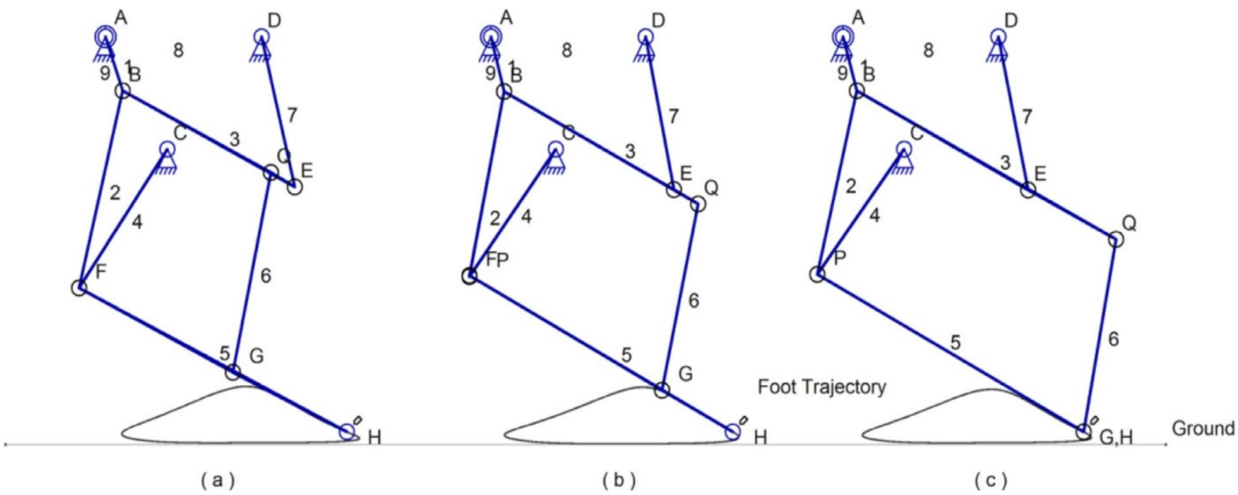


Figure 13. Second configuration of the leg mechanism.

Table 1. Length of links normalized with stridelength.

Configuration	Link1	Link2	Link3	Link4	Link5	Link6	Link7	Distancebetween G and H	DistancebetweenF and P	DistancebetweenE and Q
First	0.254	0.853	0.853	0.748	1.254	0.853	0.600	0.401	–	–
Second	0.265	0.760	0.860	0.730	1.190	0.760	0.620	Variable	–	Variable
Third	0.236	0.750	0.800	0.540	1.175	0.750	0.640	Variable	0.120	Variable
Fourth	0.027	0.750	0.900	1.050	1.560	0.750	0.700	Variable	Variable	Variable
Fifth	0.268	1.033	1.033	0.815	1.033	1.570	0.718	0.560	–	–
Sixth	0.254	0.853	0.853	0.748	1.254	0.853	0.600	0.401	–	–

Table 2. Coordinates of pivot points normalized with stridelength

Configuration	AX	AY	CX	CY	DX	DY

First	0.0	0.0	0.313	−0.487	0.708	0.0
Second	0.0	0.0	0.400	−0.400	0.687	0.0
Third	0.0	0.0	0.400	−0.300	0.618	0.0
Fourth	0.0	0.0	0.430	−0.378	0.800	0.0
Fifth	0.0	0.0	0.620	−0.663	0.852	0.244
Sixth	0.0	0.0	0.313	−0.487	0.708	0.0

4.2 Third configuration the walking leg mechanism

The third configuration of the walking leg mechanism is shown in Fig. 7(a)–(c) is almost similar to second configuration. The lower rocker arm 4 is detached from Eand connected at small distance above by a joint P on link 2. The links 2 should be parallel to 5, and 3 parallel to 6. The mechanisms foot trajectory remains the same, irrespective of the position of link 6 which is shown in Fig. 7(b) and (c). The mechanism has eight links and nine pin joints. Three of the joints are fixed and six are moving joints.

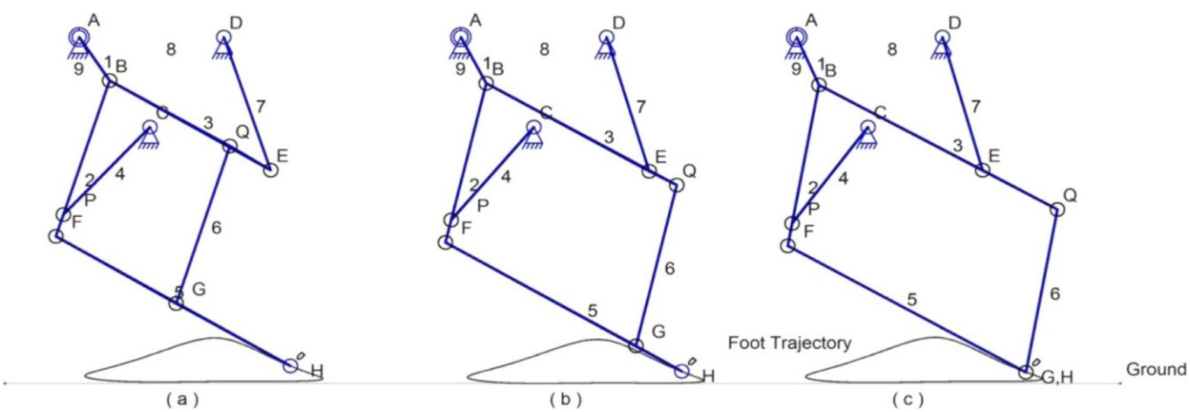
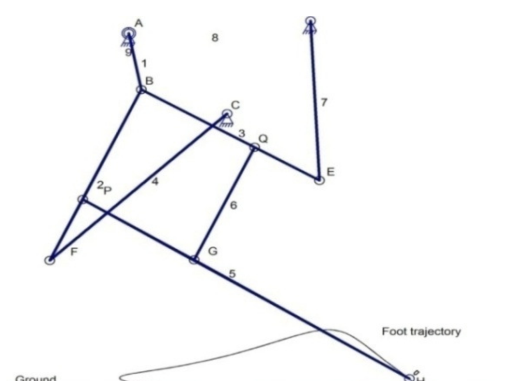


Figure 14. Third configuration of the leg mechanism.

4.3 Fourth configuration the walking leg mechanism

The fourth configuration of the walking leg mechanism is shown in Fig. 8. The modification has been done here by shifting the leg 5 joint from F to the new position P along link 2, and shifting the link 6 joint towards left along 3 from E to new position Q. The length of link 6 has been reduced. The link 2 should be parallel to link 6 and link 3 should also to be parallel to link 5. The mechanism has eight links and nine pin joints. Three of the joints are fixed and six are moving joints. This fourth configuration is compact; therefore it is light in weight.



4.4 Fifth configuration the walking leg mechanism

The fifth configuration of the walking leg mechanism is shown in Fig. 9. The modification of the present leg mechanism is performed by keeping the link dimensions unchanged and the link 6 is extended instead of link 5. The end of link 6 is a foot. The performance of this mechanism is different from the previous configurations; it suffers from locking and the velocity of the foot while moving along stride path is uneven

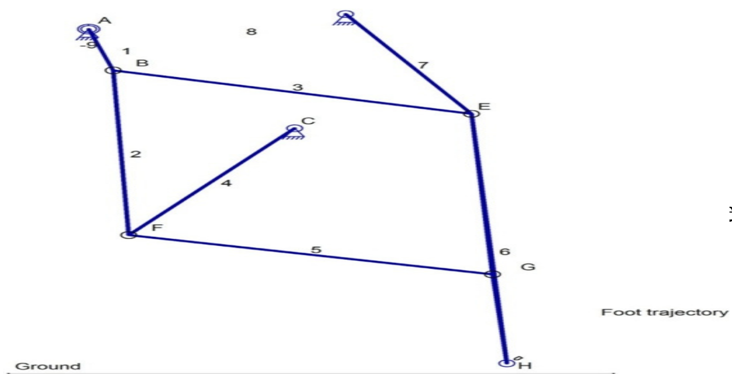


Figure 16. Fifth configuration of the leg mechanism.

4.5 Sixth configuration the walking leg mechanism

he mechanism is shown in Fig. 10. Only one link either link 2 or link 3 is rotatably connected to crankpin at B. Fig. 10(a) shows link 2 that is connected to crankpin. The modification is performed by extending link 2 above by 15% of crank length; at the end is new joint P to which link 3 is connected. In this configuration the foot has a maximum lift; however, positioning the joint P below on link 2 will reduce the lift Fig. 10(c). When the offset point P is on the left or on the right of crankpin, the stride length and lift has no effect. There is a rounding of leg tip profile at the beginning of the lift when the offset point is on the right of crankpin Fig. 10(b) and (c). In the above configuration the links 3 and 5 are not parallel, soalso the link 2 and 6.

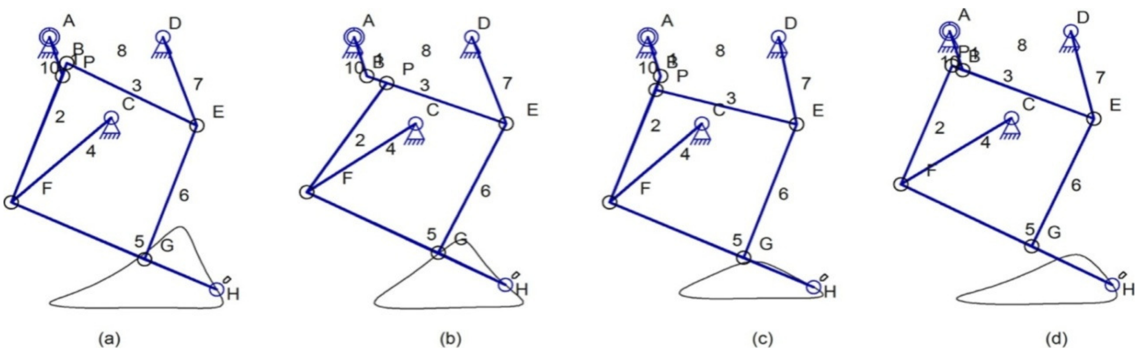


Figure 17. Sixth configuration of the leg mechanism

5. Kinematic analysis

Kinematic analysis is performed for constant crank rotation, the foot position, velocity and acceleration is calculated using algebraic methods.

5.1. Position analysis

The sketch of the walking leg linkage is shown in Fig. 11. It is possible to derive the position coordinates of foot point (H_X, H_Y) for a given crank position [24]. This requires the length of links, which can be represented as a vector

$$L = [L_1, L_2, L_3, L_4, L_5, L_6, L_7, L_8, L_9, L_{10}, L_{11}] \quad (1)$$

The orientation of the links is expressed by an angle, which is measured in counterclockwise direction from the horizontal reference. Assuming a reference at point A and analyzing the first crank rocker ABED to get the coordinates of point B as a function of input crank angle θ_1,

$$B_x = L_1 \cos\theta_1 \quad (2)$$

$$B_y = L_1 \sin\theta_1 \quad (3)$$

The coordinates of point E are calculated using the equation of circles about centers B and D,

$$L_8^2 = (E_x - B_x)^2 + (E_y - B_y)^2 \quad (4)$$

$$L_7^2 = (E_x - L_9)^2 + E_y^2 \quad (5)$$

Subtracting Eq. (5) from 4 gives an expression for E_X.

$$E_x = \frac{L_1^2 - L_8^2 + L_7^2 - L_9^2}{2(B_x - L_9)} - \frac{B_y\ E_y}{(B_x - L_9)} = S - \frac{B_y\ E_y}{(B_x - L_9)} \quad (6)$$

Substituting Eq. (6) into Eq. (5) gives a quadratic equation in E_Y which has two solutions.

$$E_y^2 + \left[S - \frac{B_y\ E_y}{B_x - L_9} - L_9\right]^2 - L_7^2 = 0 \quad (7)$$

$$E_y = \frac{-Q \pm \sqrt{Q^2 - 4PR}}{2P} \quad (8)$$

where:

$$S = \frac{L_1^2 - L_8^2 + L_7^2 - L_9^2}{2(B_x - L_9)} \qquad R = (L_9 - S)^2 - {L_7}^2$$

$$P = \frac{B_y^2}{(B_x - L_9)^2} + 1 \qquad Q = \frac{2B_y(L_9 - S)}{B_x - L_9}$$

Once E_Y is known by Eq. (8) it is then substituted in Eq. (6) and E_X is calculated. The same equations are used to calculate coordinates of F that is F_X and F_Y. Once again by using above equations coordinates of G (G_X,G_Y) are calculated.

θ_3 is an angle made by leg 5 and is given by,

$$\theta_4 = \arctan\left[\frac{G_x - F_x}{G_y - F_y}\right] \quad (9)$$

The other angles of the links are calculated with the similar procedure.

The coordinates of the foot H_X and H_Y are calculated from equations below

$$H_x = G_x + L_5 \sin\theta_4 \quad (10)$$

$$H_y = G_y + L_5 \cos\theta_4 \quad (11)$$

5.2. Velocity and acceleration analysis

The velocity and acceleration of the foot trajectory are calculated by numerical differentiation. Richardson Method is used since it is valid for cases where the increments between the independent variable time are equal. The derivative of the displacement- time curve can be numerically approximated from the following equation [25]:

$$V_x = \left[\frac{\Delta Rx_{i+1} - \Delta Rx_{i-1}}{2\Delta t}\right] - \left[\frac{\Delta Rx_{i+2} - 2\Delta Rx_{i+1} + 2\Delta Rx_{i-1} - \Delta Rx_{i-2}}{12\Delta t}\right] \quad (12)$$

$$V_y = \left[\frac{\Delta Ry_{i+1} - \Delta Ry_{i-1}}{2\Delta t}\right] - \left[\frac{\Delta Ry_{i+2} - 2\Delta Ry_{i+1} + 2\Delta Ry_{i-1} - \Delta Ry_{i-2}}{12\Delta t}\right] \quad (13)$$

$$A_x = \left[\frac{\Delta Vx_{i+1} - \Delta Vx_{i-1}}{2\Delta t}\right] - \left[\frac{\Delta Vx_{i+2} - 2\Delta Vx_{i+1} + 2\Delta Vx_{i-1} - \Delta Vx_{i-2}}{12\Delta t}\right] \quad (14)$$

$$A_y = \left[\frac{\Delta Ry_{i+1} - \Delta Ry_{i-1}}{2\Delta t}\right] - \left[\frac{\Delta Ry_{i+2} - 2\Delta Ry_{i+1} + 2\Delta Ry_{i-1} - \Delta Ry_{i-2}}{12\Delta t}\right] \quad (15)$$

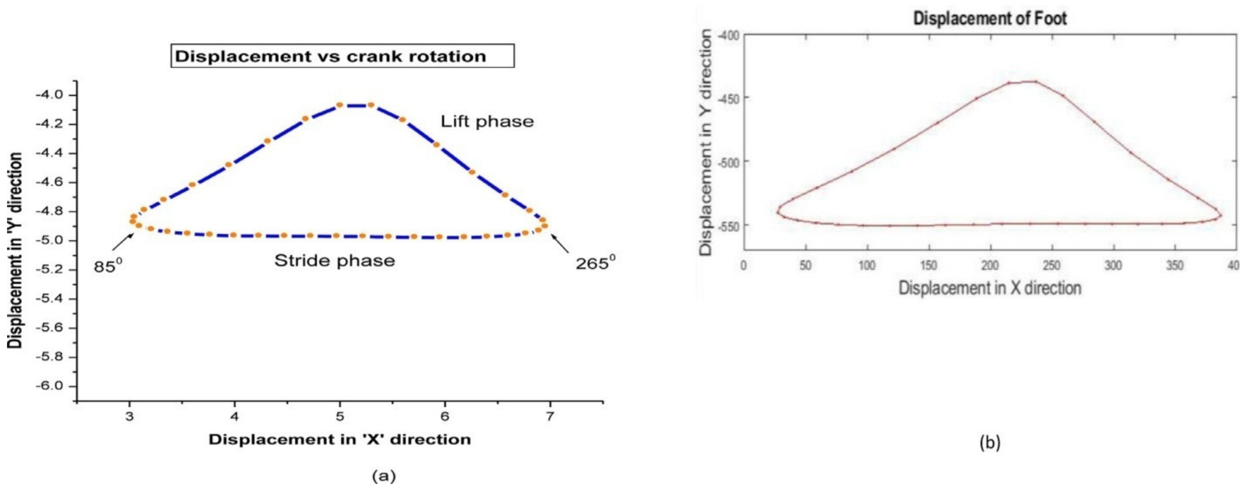


Figure 18. (a)Displacement of foot in‘X’and‘Y’directionsvs.Crank rotation.(b)MATLAB simulation of displacement

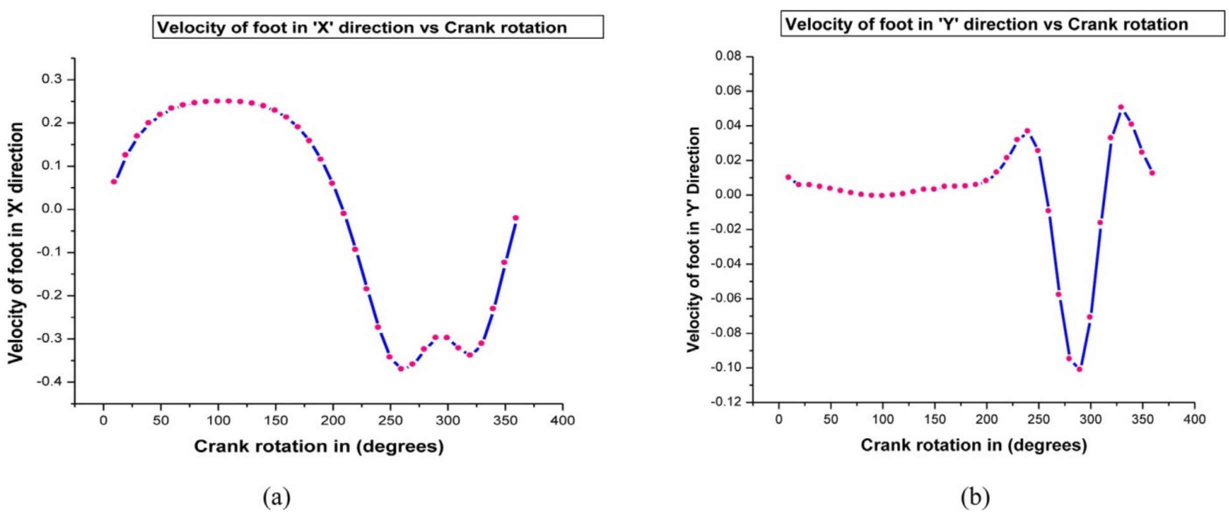


Figure 19. Velocity of the footin‘X’and‘Y’directionsvs.crankrotation.

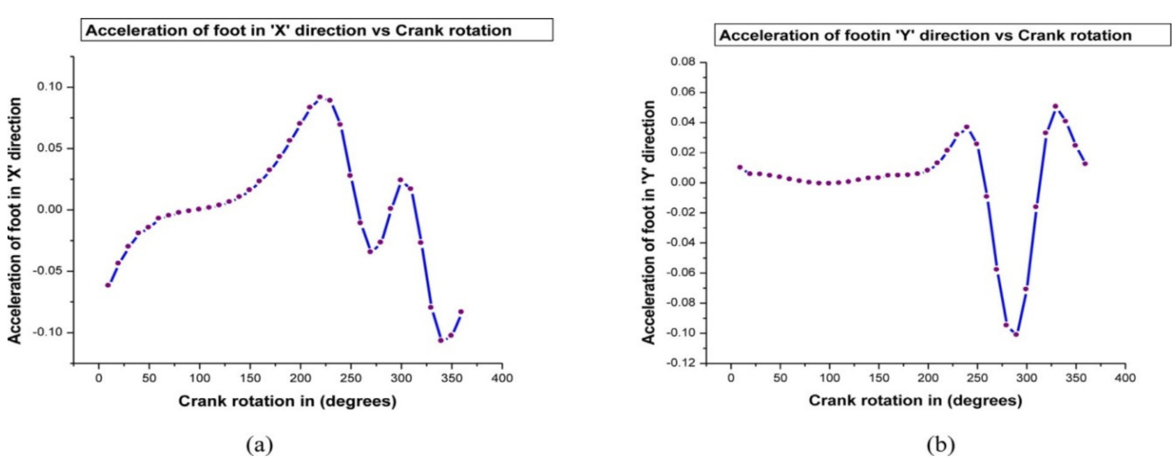
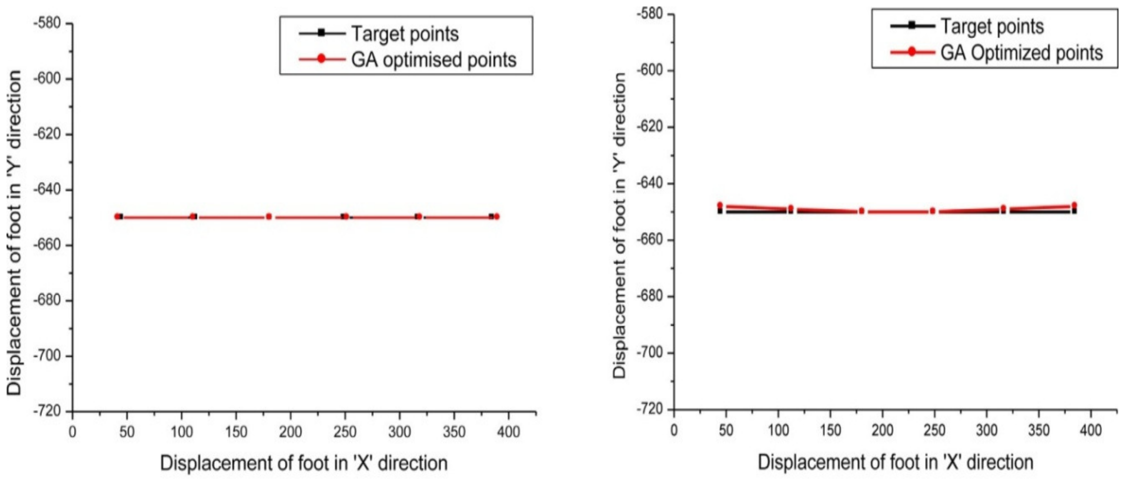


Figure 20. Acceleration of thefootin‘X’and‘Y’directionsvs.crankrotation



(a) (b)

Figure 21. Targetpoints and optimized points of foot.Displacement of foot in (a)Xdirectionand(b)Ydirection.

5. EXPERIEMNTAL RESULTS AND DISCUSSION

5.1 Experiment

The main aim of the experiment was to determine the practical accuracy of the leg mechanism. The two factors of importance are, the first is, whether the mechanism has the same profile as obtained by simulation and calculation and the second is to ascertain if the mechanism is reversible. Since two crank rockers are used in the mechanism, and both are Grashof's type, there will be no problem in forward motion (when the crank drives the leg), however, in reverse motion (when leg drives the crank) it is important to see if there is locking or jamming at toggle positions. Walking machine using this leg mechanism must behave like wheeled vehicle; the legs should move the machine with ease.

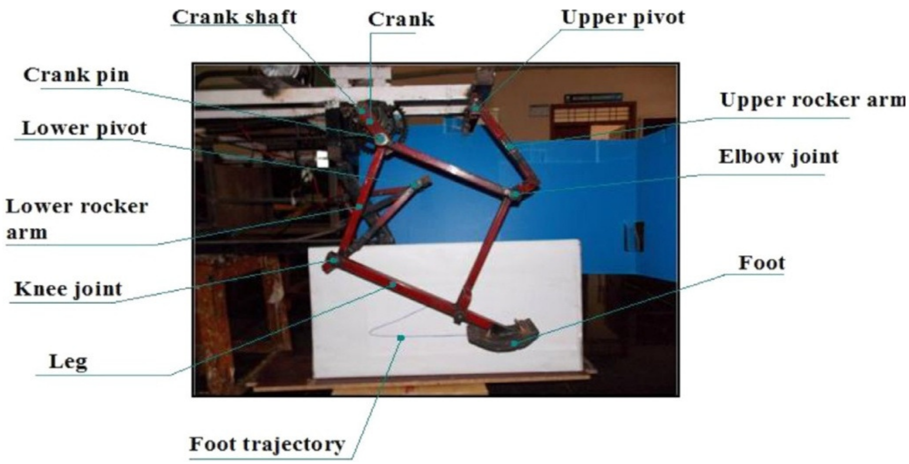


Figure 22. Experimental model of the leg mechanism..

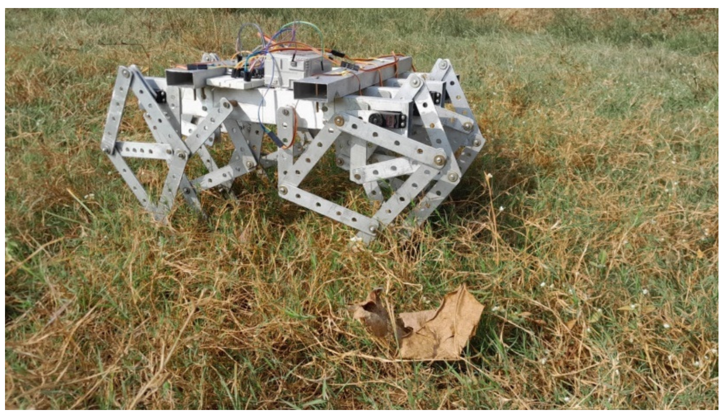


Figure 23. CADmodel of an eight leg walking machine

5.2 Experiment setup

The experiment was performed by rotating the crank by one complete rotation in increments of 5o counter-clock-wise. The stylus attached to the foot traced the trajectory and the coordinates of the foot are recorded. The second test for reversibility and locking of mechanism due to toggle position is performed by moving the foot along the stride path and the motion transfer to the crank is examined. The walking machine was also tested by manually pushing the machine.

5.3 Experiment results

The trajectory of the foot is traced, the stride length was 370 mm and stride height was 110 mm. The locus of the foot was compared with the simulation and analytical calculations as shown in Fig. 19(a) and (b). The locus of the foot and simulation trajectory has almost the same value compared with the experimental value, with small errors,owing tothe clearancebetween joints and fabrication errors.

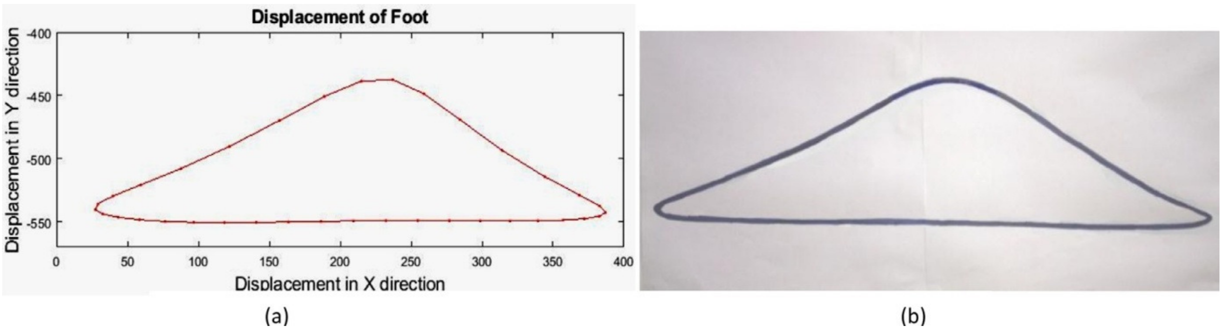


Figure 24. (a) Foot trajectory by simulation and (b) by tracing.

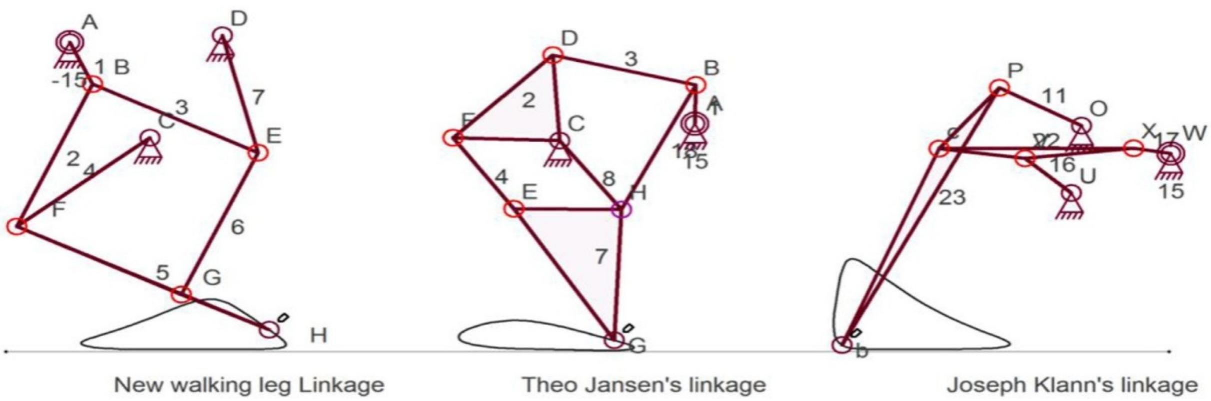


Figure 25. Foot profile of then ew mechanism, Klann'sandJansen'slinkage

Table 3. Comparison of walking leg mechanism with Klann's and Jansen's linkage.

No	Criterion	Klann'slinkage	Jansen'slinkage	Proposedwalkinglegmechanism
1	Nooflinks	6	8	8
2	Noofsupportpivotstotheframe	3	2	3
3	Errorpercentageinstraightnessofstridepathtostridelength	3.40	0.050	0.037
4	StridelengthtoSizeofmechanism	Medium	Large	Compact
5	Thevelocityoffootwhiletrendingstridepath	Fluctuating	Nearlyconstant	Fluctuating
6	Flexibility	Limited	Limited	Highlyflexible
7	Directionofrotationofcrank	Clockwise	Counter-clock-wise	Canoperateinbothdirections
8	Stridetotransferratio	0.47	0.63	0.486
9	Stridelengthtosizeofmechanism	Medium	Medium	Large

7.Conclusion

A new walking leg mechanism is presented. The geometry and working are explained. Kinematic analysis and simulation is performed by MATLAB and Linkage 3.0. The results of kinematic analysis are used in optimization. The experimental model of both mechanism and walking machine is built and tested for its practical accuracy. The mechanisms analytical results are compared with simulation and also compared with foot trajectory traced by the fabricated model. The mechanism is compared with Klann's and Jansen's linkage and the differences are listed. Advantages of the proposed leg mechanism are,

- The mechanism is mounted on a frame having three fixed pivots make it strong and stable.
- The proposed mechanism can be constructed with binary links only, although it can also be constructed using ternary and quaternary links.
- The mechanisms foot has ground contact for 180o rotation of the crank and 180o for the lift makes it economical. Any walking machine using this mechanism requires only two legs to substitute a wheel.
- The walking mechanism can be built compactly and hence weigh less and less inertia, and therefore it is suitable for speed walking.
- The mechanism performs quite well for both clockwise and anti-clockwise rotation of the crank.
- The stride length and height can be increased or decreased by changing the distance between the three fixed joints, by changing the distancebetween the crankshaft and the upper rocker pivot or the lower rocker pivot or both.
- This mechanism has largest stride to size ratio. The limitation of the proposed mechanism is that it is not possible to put the linkage pair in the same plane as Jensen's and Klann's linkage. Practical application of this walking leg mechanism can be in industries, agriculture, recreation, autonomous vehicles, all-terrain vehicles, robots, toys and the like.

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