IFToMM

TENTH WORLD CONGRES
ON THE THEORY OF
MACHINES AND MECHANIS.

PROCEEDINGS

Vol. 2

MECHANISMS
MICROMECHANISMS

UNIVERSITY of OULU

University of Oulu, Finland
June 20 - 24, 1999

TENTH WORLD CONGRESS ON THE THEORY OF
MACHINES AND MECHANISMS
Oulu, Finland, June 20-24, 1999

KINEMATIC AND KINETOSTATIC SIMULATION OF A LEG MECHANISM

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Key words: Leg mechanism, path generator, motion inversion, kinetostatic analysis

1. Introduction

In the field of mechanical design there are numerous studies available on mobile robots and walking machines. The interest in this type of mechanical locomotion derives from the superior mechanical advantage and greater adaptability when travelling on uneven terrain, in comparison to wheeled and tracked mobile robots.

The topology of a leg mechanism to be used in a walking machine must comply with the intended performances and with the control scheme employed. Among these, planar single and double degree-of-freedom linkage mechanisms, have received a great deal of attention [Tao and Fu 1989] [Kopp 1994]. The second degree-of-freedom, if available, can participate continuously in generating the foot trajectory [Kheddar et al.], or as an adjusting degree-of-freedom destined to make the foot motion comply with the terrain irregularities [Tao and Fu 1989] [Williams et al 1991].

There are cases when single DOF leg mechanisms provide sufficient versatility and control to robot propulsion. Possible applications are the planar four-bar curve generators with a rectilinear portion of the coupler-curve, like Chebyshev's, Grasshopper's and Hoecken's mechanisms [Eraslan 1979], or open, approximately straight-line path generators, like those of Evens, Watt and Roberts [Ryan and Hunt 1985]. The former category of straight line path generators must be amplified with some inversors or pantograph linkages, in order to revert the orientation of the return stroke towards the platform [Williams et al 1991]. The later category have the drawback that the motion of the input member must be an oscillating one (rotation or translation). Moreover, a means of adjusting the foot height when in return must be provided, which actually turns such leg mechanisms into two degree-of-freedom ensembles.

2. Six-bar leg mechanisms

Watt and Stephenson double loop mechanisms have been investigated as leg mechanisms by Kopp [Kopp 1994]. In the same reference design recommendations can be found for synthesising D-shape six and eight-bar path generators. Two such mechanisms will be briefly discussed in connection with figures 1 and 2-a.

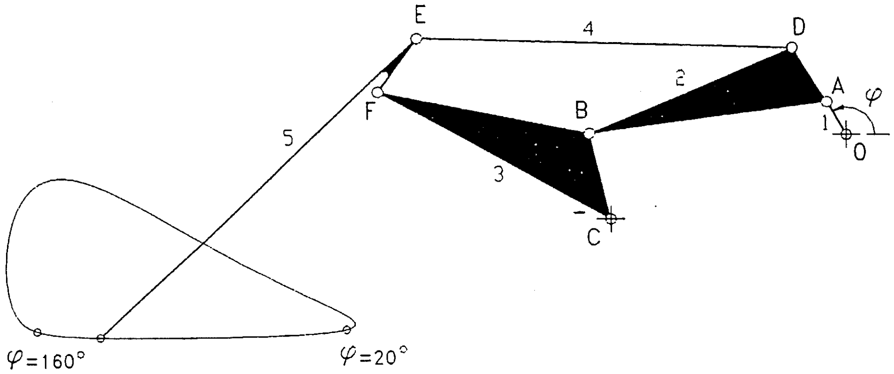


Figure 1. Watt I D-shape asymmetric path generator proposed as leg mechanism in [Kopp 1994] (the robot moves to the right when the crank 1 rotates counter-clockwise).

The mechanism in figure 1 is capable of generating an asymmetric D-shape couple curve. At the link proportions shown, the approximately rectilinear region of the foot-path corresponds to one third of the crank rotation. This feature makes it suitable for six-leg crab-like walking machines, the risen left part of the foot-path supplementary ensuring an obstacle climbing ability of this type of mechanism.

A second leg mechanism proposed by Kopp is shown in figure 2-a. This is a symmetrical mechanism (a variant of Peaucellier's inversor), and has the feature that the rectilinear portion of the foot-path is travelled for half of the input-crank rotation range [180° ≤ φ ≤ 360°]. It is therefore suitable for applications in biped and quadruped walking machines. By amplifying it with an RRT dyad (as shown in figure 2-b), its suppleness can be improved, and also the pivot joint labelled F becomes less exposed, being now higher above the ground. Because rotational joints are easy to maintain and cope better in a dirty environment, they are preferred to sliding joints. In this respect the variant in figure 2-b is less attractive than the original solution. A similar observation can be made when comparing rectilinear or rotational output actuating motors. It is also advantageous to have these motors on the robot platform, which is easier to control and allows a lighter leg arrangement.

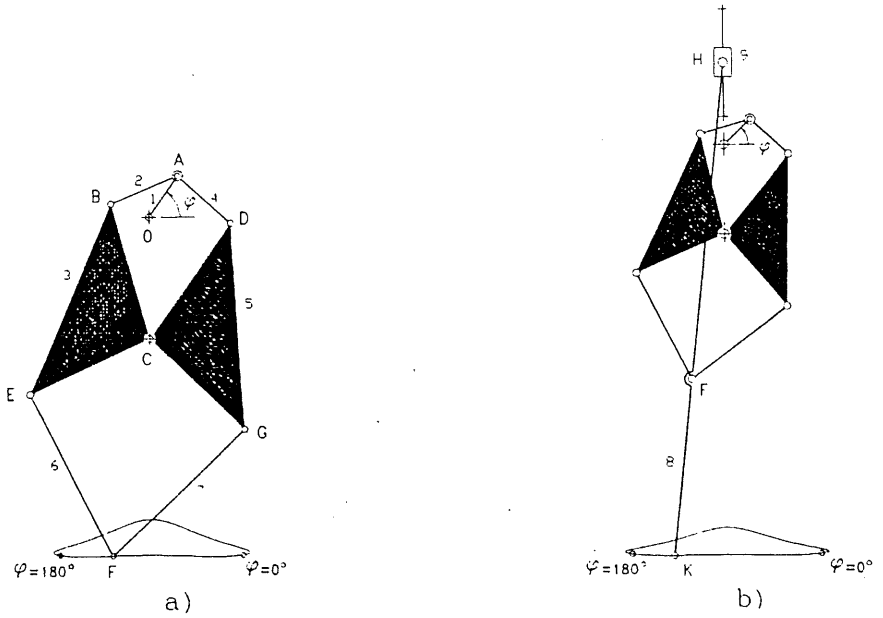
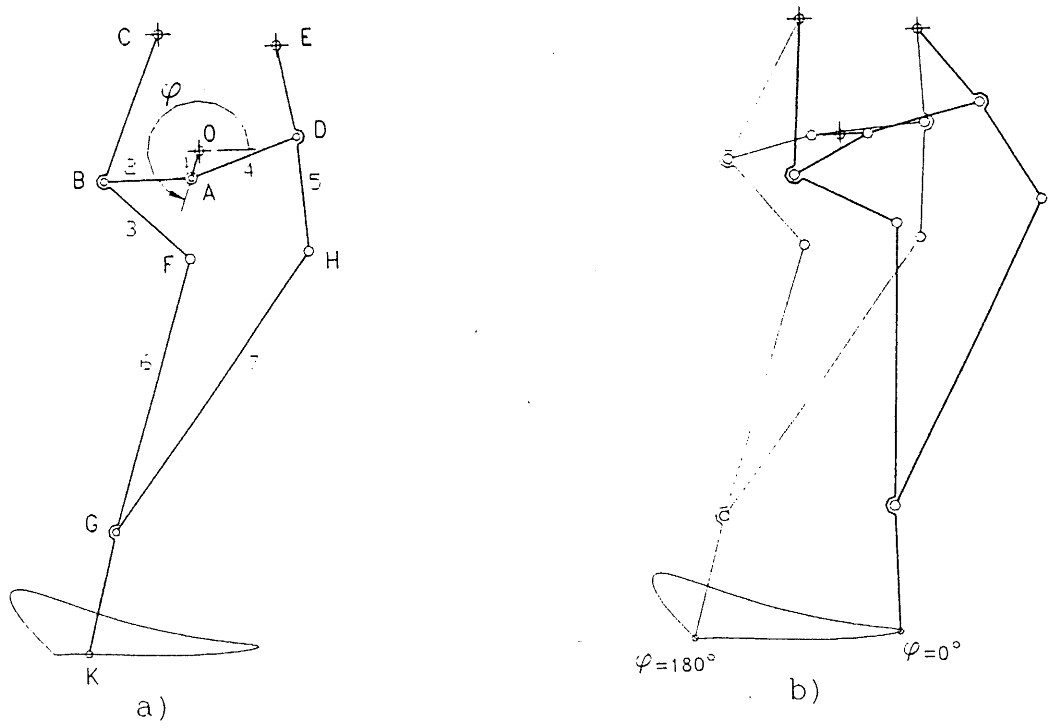


Figure 2. a) Symmetrical leg mechanisms derived from Peauceller's inversor (after [Kopp 1994]). b) The same mechanism amplified with an RRT dyad destined to increase the ground clearance and suppleness.



a)

b)

Figure 3. a) Leg mechanism derived from Watt II linkage amplified with an RRR dyad. b) Representation of the mechanism in the two extreme positions of point K along the rectilinear trajectory of the foot path

A second leg mechanism proposed by Kopp is shown in figure 2-a. This is a symmetrical mechanism (a variant of Peaucellier's inversor), and has the feature that the rectilinear portion of the foot-path is travelled for half of the input-crank rotation range ($\varphi \in [180°..360°]$). It is therefore suitable for applications in biped and quadruped walking machine. By amplifying it with an RRT dyad (as shown in figure 2-b), its suppleness (sliminess?) can be improved, and also the pivot joint labelled F becomes less exposed, being now risen above the ground.
Because rotational joints are easy to maintain and cope better in a dirty environment, they are preferred to sliding joints. In this respect the variant in figure 2-b is less attractive than the original solution. Similar observation can be made when comparing rectilinear or rotational output actuating motors. It is also advantageous to have these motors disposed on the robot platform, which brings to an easier control and to a lighter leg arrangement.

3. Kinematic features of the proposed mechanism

The leg mechanism proposed has a topology identical with Kopp's second mechanisms (figure 2-a). It consists of a Watt II linkage amplified with an RRR dyad, driven by a relatively short crank, marked 1 in figure 3-a.
Through a trial-and-error search, using the mechanism simulation software OSMEC, a set of link lengths have been determined such that the foot centre K describes an elongated trajectory with a suitable timing. From the diagrams in figure 4 it can be seen that the foot moves slowly when in contact with the ground for half the kinematic cycle, but faster on the return stroke. For the input crank uniformly driven, the speed and acceleration of the foot point K approaches zero over the interval $\varphi \in [180..360]$ (figure 4-b), a consequence of the almost rectilinear shape of the lower part of the foot locus. When the robot moves to the left (see figure 3), the foot path favourably approaches the ground at an obtuse angle, which

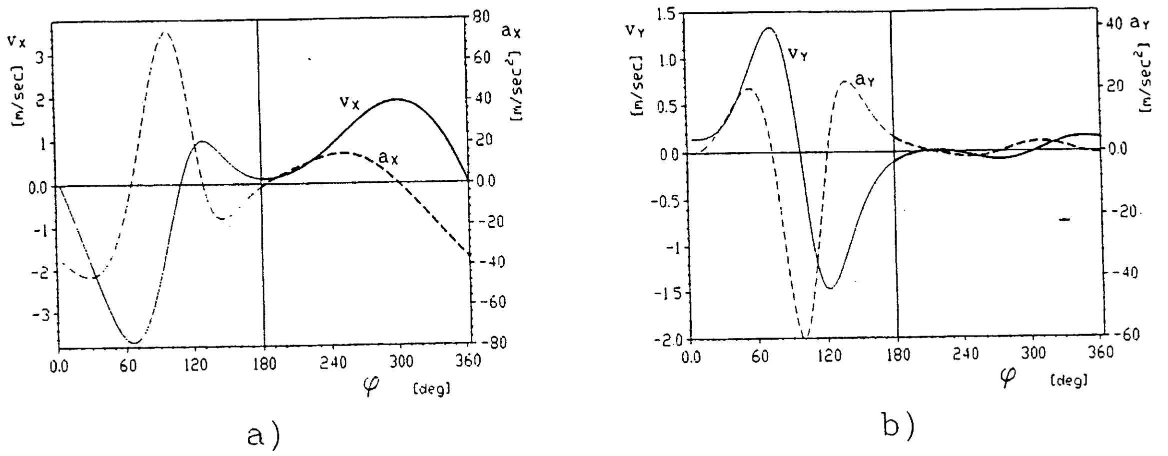


Figure 4. Foot point centre K a) horizontal and b) vertical speed and acceleration corresponding to a constant speed of input crank of 100 rpm

permits compensating the speed difference that might appear, and also permits some small obstacle climbing, features that are likely to ensure a smooth propulsion of the robot.
A similar foot trajectory has been generated through a 2 DOF mechanism by the authors of paper [Kheddar et al 1994], in the case of a hybrid mobile robot with two legs in tandem with two wheels disposed on the same shaft. Even though the leg mechanism is simpler than the present one, the whole appliance is complicated by the use of two pneumatic actuators, while the "on-off" control does not put into value the extra degree of freedom available for improving the ground irregularity compliance.

4. Kinetostatic simulation of the leg mechanism

Dynamic modelling and stability control of a legged vehicle is a difficult task and has been addressed by several researchers in the past [Freeman and Orin 1991] [Kumar et al 1990] [Zhang et al 1994]. In the case of an autonomous robot, to properly specify the actuating motors, power source, and leg part's dimensions, it is important to estimate the required input

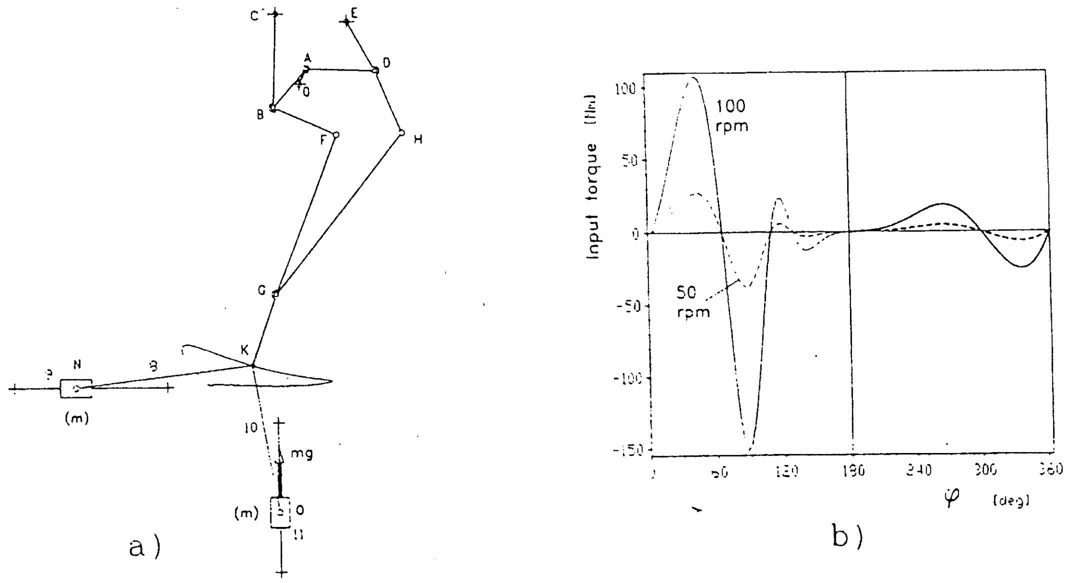
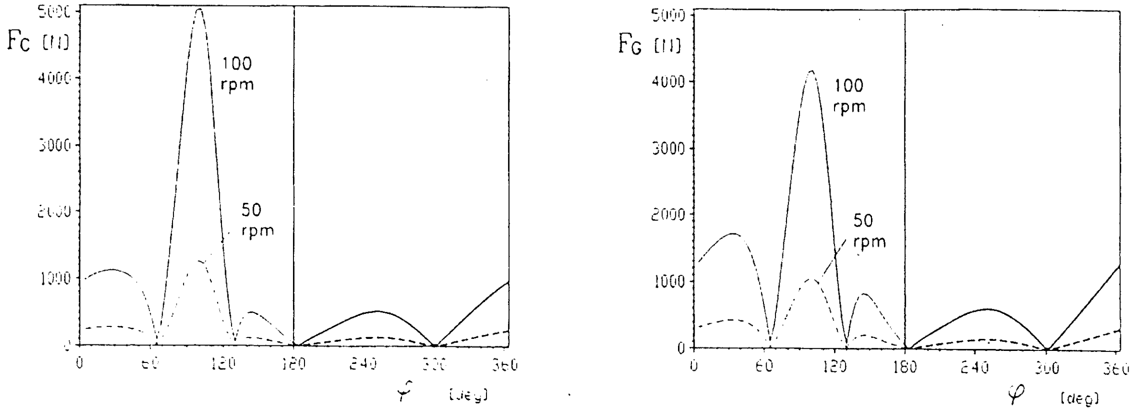


Figure 5. a) Kinetostatic model of the leg mechanism. b) Required input torque for a constant crank 1 speed of 50 and 100 rpm respectively.



a) b)

Figure 6. Reaction forces developed in a) joint C and b) joint G of the leg mechanism for 50 and 100 rpm input crank speed

torque and the pick reaction forces possible to occur in the joints.

For this matter, a simple kinetostatic model was developed, which permits approximating the torque required for constantly driving the input crank at a given speed. Considering one leg only, a motion inversion was applied in which the platform is maintained steady, with the whole robot risen above the ground. The OSMEC software permits associating masses and moments of inertia to each moving element, but for a first approximation, these were considered negligible. Only the inertial and gravitational effects of the mass of the robot platform was considered.

These effects were modelled by jointing two RRT coupler-slider dyads (marked 8-9 and 10-11 on figure 5) to the foot centre K, of which one slider track is oriented vertically and the other horizontally, as shown in figure 5-a. An equivalent masses m was attached to each slider, representing the inertial effect of the fraction of the robot platform upon each of the robots leg. In addition, a constant force $m\cdot g$ was applied to the vertically oscillating slider (11), oriented upwards, which models the ground reaction force upon the foot point K (g=9.81 m/s^2 is the acceleration due to gravity). In order to diminish the effect of the pressure angles in joints N and Q, which vary through a kinematic cycle, upon the inertia forces and to increase the realism of the simulation, the couplers 8 and 10 were considered several times longer than the overall gauge of the robot.

5 Numerical results

Considering the fraction of the weight of the robot platform distributed to one leg m=10kg, and for two constant input speeds of the driven motor of 50 and 100 rpm, the required torque to be input at the crank 1 varies as in figure 5-b. The significant part of the diagram is the half right hand, corresponding to the input angle ranging between 180 and 360 degrees (the active stroke), for which the foot maintains contact with the ground. By numerically integrating under these curves an average travelling speed of 1.77 and 3.55 m/sec were obtained.

For the two speeds of 50 and 100 rpm of the motor, the maximum positive torque required, when the foot is in contact with the ground, was found to be 63 and 380 Nm respectively. Apparently, a doubling of the travelling speed increases six times the pick power absorbed from the battery supply.

The OSMEC software permits the determination of numerous kinematic and kinetostatic parameters of the mechanism, like the reaction forces occurring in the joints. In figure 6 are examples of the variation of the magnitude of the forces occurring in joints C and G, for both 50 and 100 rpm of the input crank. These values are useful in designing the bearing joints and of the leg elements cross-sections.

Conclusions

A new single degree of freedom leg mechanism has been proposed, the foot-loci shape and its velocity and acceleration makes it suitable for a biped or quadruped walking machines. A simple kinetostatic inversion and equivalation of inertial and gravitational effect has been further proposed, which permits approximating of the required driven torque and of the loads possible to occur in the link joints. Experimental investigations must however be carried out in order to asses the degree of realism of this kinetostatic model.

Acknowledgements

The authors would like to thank Dr. Samuel Molian the author of OSMEC for generously gifting a copy of this software. Thanks are also extended to Mr. Paul Aitken for his help in preparing the final version of the paper.

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