CHINESE JOURNAL OF MECHANICAL ENGINEERING
Vol. 24, No. 5, 2011

DOI: 10.3901/CJME.2010.05.***, available online at www.cjmenet.com; www.cjmenet.com.cn

Adjustable Mechanism for Walking Robots with Minimum Number of Actuators

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Received December 23, 2010; revised July 6, 2011; accepted July 11, 2011; published electronically July 12, 2011

Abstract: Recent literature on walking robots deals predominantly with multi-degrees-of-freedom leg mechanisms and machines capable of adopting several gaits. This paper explores the other end of the spectrum suggesting mechanisms derived from a four bar coupler curve for a one degree of freedom walking robot. Simulation of the walk indicates that body of the robot is able to move with low variation in velocity. The best strategy for changing the gait to enable the robot to walk over obstacles and the effect of change in length of different links are explored to open up the possibility of a two degree of freedom walking robot with the capability of changing its gait, suitable as a low cost unit for several applications. Such rugged units would permit the use of an IC engine as the primary source of power and could be of utility in installations where electronics may not be functional. In simple walking machines the foot of a leg is usually required to trace a *D* shaped curve with respect to the chassis. In this paper we begin with a Hoecken mechanism capable of tracing such a curve. The foot is required to move parallel to itself and the same could be achieved using a six or eight link mechanism. A few such devices have been synthesized in this paper and their motion properties compared. The study also covers the possibility of providing adjustments to vary the step length and height of the foot's movement.

Key words: walking robot, degree of freedom, coupler curve, gait

1 Introduction

While designing a walking robot, one of the first decisions pertains to a selection of the degrees of freedom of each leg[1]. A design with legs possessing several degrees of freedom leads to the ability to walk with several gaits and negotiate complex terrains. The large number of actuators leads to an increase in weight and the additional sensors may reduce the robustness. Reduction in the degrees of freedom reduces both the number of gaits available as also the robot's ability to negotiate different types of terrain. Walking robot designers have tried to solve this dilemma by mechanical coordination of motion[2]. However, a search of literature reveals that simplification of design and reduction of the degrees of freedom has been accompanied by a less than ideal trajectory for the leg of a walking robot (VINAYAK and SEN[3]). The ideal trajectory would be a "D" with the straight side of the "*D*" facing the ground and a constant velocity in this straight portion. This can be attained at present only by walking robots with multi-degrees of freedom legs - examples being Honda's Asimo[4] and Nataraj[5]. A related problem is to be able to change the gait with as few additional actuators as possible. Usually, a change in gait is possible only in cases where a large number of actuators are available, a few examples being the robots described by HIROSE, et al[6] and YONEDA, et al[7].

This paper provides a simple modification to a well known mechanism to obtain a nearly ideal trajectory for the legs of a walking robot. It suggests how mechanical coordination can be used to make the robot walk with only one actuator. It then explores the best strategy to change the gait by using a single additional actuator. The changes in velocity, acceleration and jerk with change in gait are also investigated.

2 Towards an Ideal Walking Mechanism

2.1 The four bar coupler curve

From the point of view of reliability, it would be preferable to design the legs of a walking robot with only revolute pairs and avoid prismatic pairs. Since reduction of complexity is one of the prime objectives of a designer, the four bar linkage would be ideal for a leg, provided a suitable coupler curve is available. The ideal coupler curve would be in the form of a "*D*" with the straight side of the *D* facing away from the mechanism envelop. In addition, a nearly constant velocity in the straight portion of the *D* would be preferable. Unfortunately, no four bar coupler curve satisfies these criteria. The closest one can get is with the Hoecken's mechanism (Fig. 1)[8]. The ratios of link lengths are given as follows:

AB=100, BC=250, CD=250, AD=200, CE=250.

The coupler point E lies in-line with the coupler BC. The two diagrams in Fig. 1 show the mechanism at two positions of the crank AB, 180° apart. The coupler curve is in the form of a *D* and the velocity of the coupler point "*E*" is nearly constant in the almost straight portion of the *D*.

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But the straight side of the *D* faces the mechanism. This means that if this is used a leg of a waking robot, then the transfer phase would correspond to the curved portion of the *D*. This is not preferable because it would introduce an unnecessary vertical displacement of the robot's body and there would be considerable variation in velocity during each cycle.

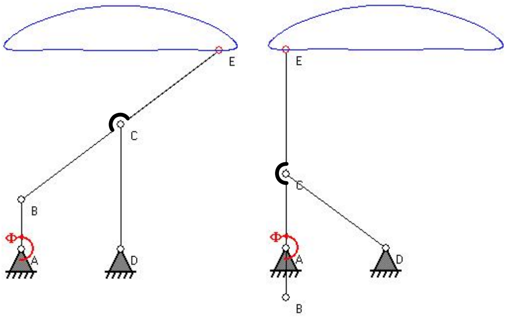

Fig. 1. Hoecken's mechanism in two positions

2.2 Modification of the Four Bar

The ideal solution would be to transpose the coupler curve of the Hoecken's mechanism to a position below the mechanism in Fig. 1 without changing its orientation. This section explores four ways of achieving this, two of which result in six bar mechanisms and the other two result in eight bar mechanisms.

The first strategy was to take advantage of cognates of the Hoecken's mechanism. The two cognates are shown in Fig. 2. The Hoecken's mechanism has been shown in a position in which the crank *AB* is 90° ahead of the position shown in Fig. 1 for ease of visualization.

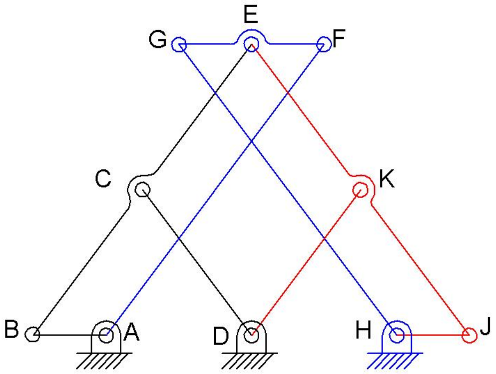

Fig. 2. Hoecken's mechanism with its two cognates

The mechanism *AFGH* is called the left hand cognate in which the coupler point *E* on the coupler *FG* traces the same curve as the coupler curve of the original mechanism (*ABCD*). The angular rotation of the links *CD* and *GH* are the same. Similarly, the mechanism *HJKD* is called the right hand cognate in which the coupler point *E* on the coupler *JK* traces the same curve as the coupler curve of the original mechanism (*ABCD*). The angular rotation of the links *AB* and *HJ* are the same.

Let the right hand cognate be translated without rotation such that the pivot H coincides with the pivot *A* and the links *AB* and *HJ'* are conjoined to form a single ternary link as shown in Fig. 3.

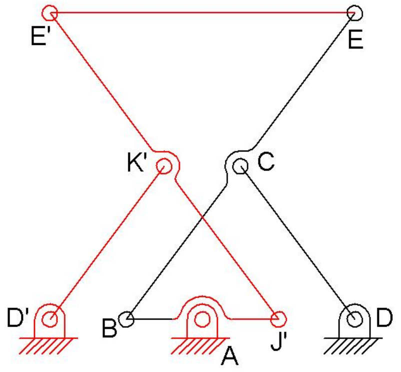

Fig. 3. Hoecken's mechanism with its right cognate suitably translated

The coupler point of the right hand cognate (E') continues to trace the same coupler curve as E in the original mechanism. Thus, a link can be used to join E and E' and this link will always remain parallel to itself. This, however, results in an over-constrained mechanism. The redundant constraints can be removed by removing the link D'K' (Fig. 4). The resulting mechanism is a single DoF six link mechanism in which the link EE' remains parallel to itself. Any point on this link or its extension will trace the same coupler curve as the coupler point E of the original Hoecken's mechanism. The point L in Fig. 4 is such a suitably placed coupler point which allows the coupler curve the Hoecken's mechanism to be replicated so that the straight section of the *D* faces away from the mechanism's envelop.

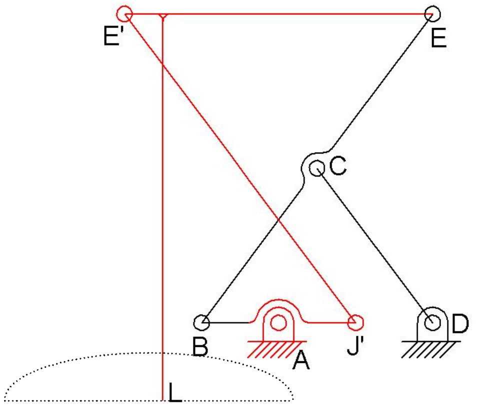

Fig. 4. Mechanism derived from the right cognate

A similar procedure can be used for deriving a mechanism from the left cognate. The resulting mechanism is shown is Fig. 5 with L as the required coupler point.

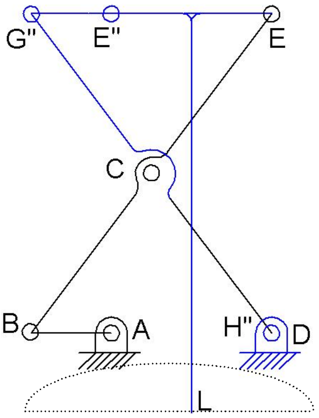

Fig. 5. Mechanism derived from the left cognate

Two more ways of replicating the coupler curve of Hoecken's mechanism in a suitable position are shown in Figs. 6 and 7. Both of these are single DoF eight link mechanisms in which the coupler curve of Hoecken's mechanism is replicated at L.

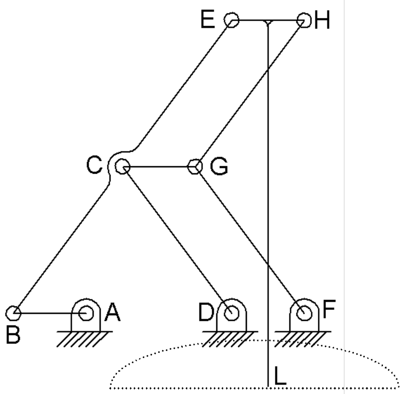

Fig. 6. Hoecken's mechanism with two parallelograms

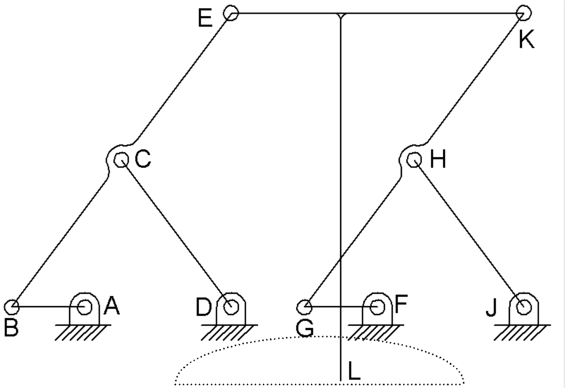

Fig. 7. Two Hoecken's mechanisms

The point L of any of the mechanisms shown in Figs. 4, 5, 6 and 7 can form the end point of one of the legs of the robot. Three (or four) such legs can be attached to three (or four) corners of the body of a robot and their motions can be synchronised by driving their cranks from the same shaft. Three (or four) more legs can be attached close to these. The cranks of the latter trio (or quartet) can be 180° out of phase with the cranks of the former. All six (or eight) legs can be driven from the same shaft – thus making it a single degree of freedom walking robot.

2.3 Simulation

Such a robot with eight legs was simulated in a mechanism simulator (ADAMS) and was found to walk as expected. One quartet of legs is always on the ground (stance phase), thus providing the robot good stability. The other quartet is always in the air (transfer phase). The body of the robot is always parallel to the ground. The quartet on the ground always executes the straight portion of the D of the coupler curve, thus giving the body of the robot a smooth motion. This is seen in Fig. 8 where the velocity of the robot's body has been plotted for one complete cycle. By comparing it with the velocity of the coupler point of a Hoecken's mechanism (Fig. 9), it is seen that the 0 to 180° section of the curve in Fig. 9 is replicated twice during each of the stance phases of the total walking cycle (Fig. 8). The small differences are due to high but finite damping at contact points between legs and ground in the simulation environment, leading to a small bounce of the robot's body. This confirms that the advantage of using the nearly straight portion of the coupler curve is indeed available.

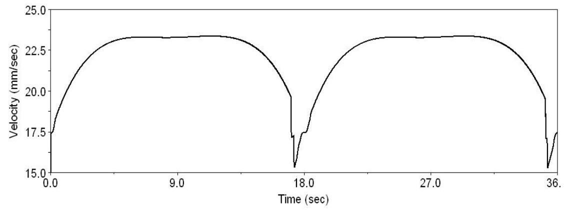

Fig. 8. Velocity of robot's body for one complete walking cycle

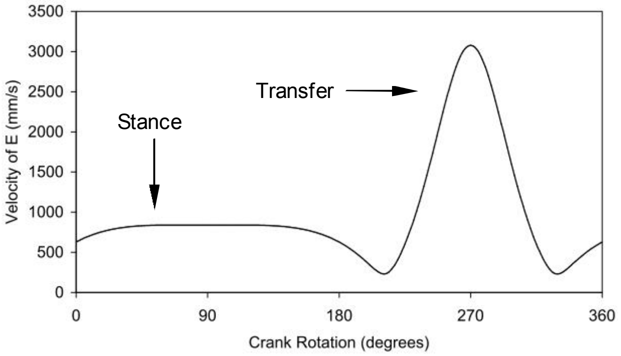

Fig. 9. Velocity of coupler point (E) of Hoecken's mechanism

Fig. 10 gives the isometric view of the mechanism in the simulation environment. The legs were mounted far apart on the chassis for troubleshooting and the mechanism shown in Fig. 7 was used for this exercise. A more compact mechanism with the legs placed closer would possess same characteristics. This is a single degree of freedom walking robot executing a single gait. The fact that the coupler curve of the Hoecken's mechanism is symmetrical about a vertical axis, contributes to the smoothness of motion of the robot.

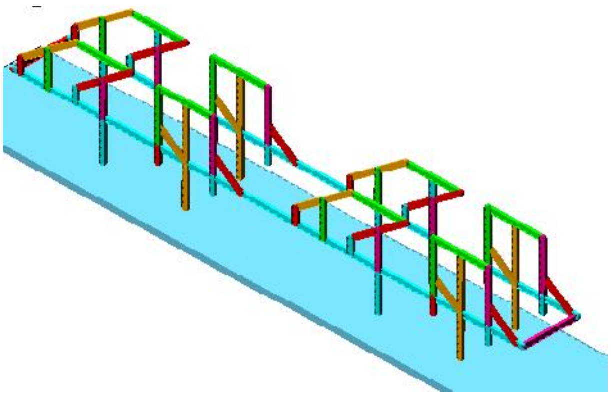

Fig. 10. Robot in the simulation environment

3 Changing the Gait Parameters

The next objective was to determine the best strategy to change the gait parameters. A typical reason to change the gait parameters would be to overcome obstacles. This would need the step height to be increased with a possible change in horizontal step length being acceptable. This would require a coupler curve with greater height and, if necessary, lower width. The most preferable way of achieving this is to change the length of only one of the links of the Hoecken's mechanism. It would be preferable to change the coupler curve in such a way that the changed coupler curve remains symmetrical about a horizontal axis.

3.1 Identification of the adjustable link

Small changes were made in the lengths of all the links of the Hoecken's mechanism and their effect on the coupler curve was observed (Figs. 11 to 15).

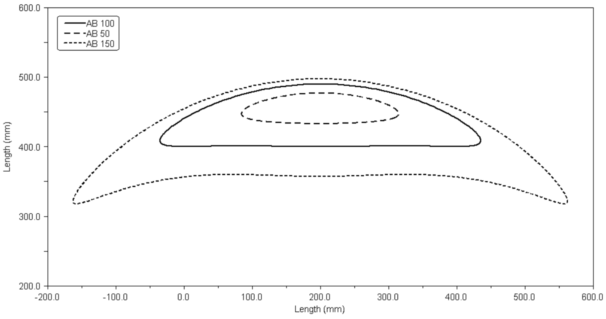

Fig. 11. Effect of change in length of crank (*AB*) on coupler curve

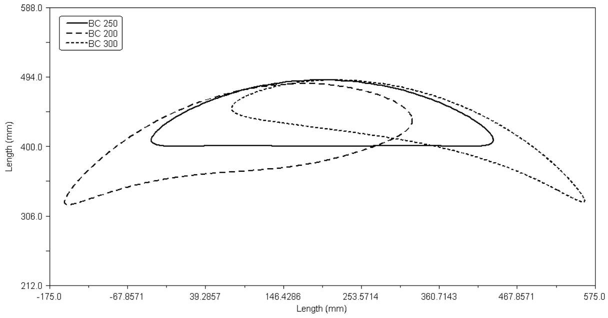

Fig. 12. Effect of change in length of coupler (*BC*) on coupler curve

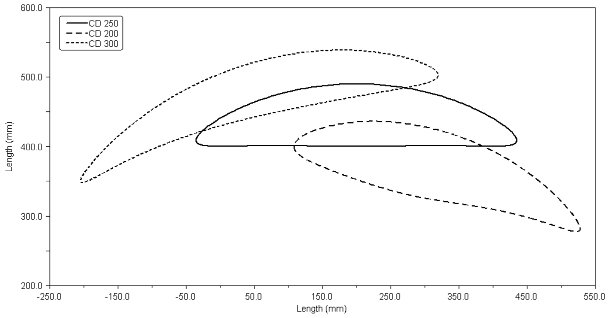

Fig. 13. Effect of change in length of rocker (*CD*) on coupler curve

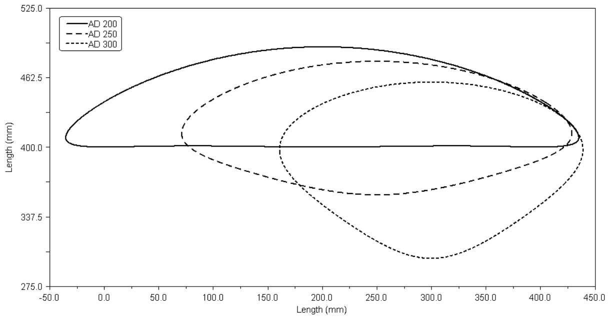

Fig. 14. Effect of change in length of ground link (*AD*) on coupler curve

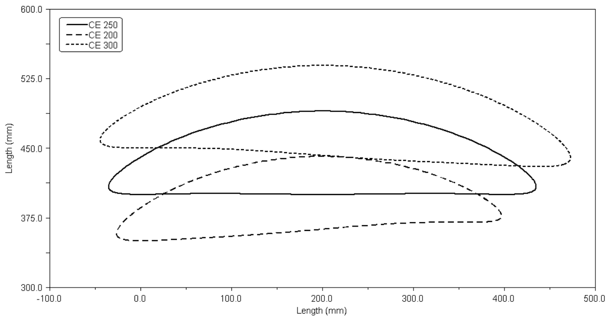

Fig. 15. Effect of change in length of extension to coupler (*CE*) on coupler curve

It is seen that an increase in length of the crank (*AB*) will produce the desired change (Fig. 11). The changed curve has greater width and height compared to the original curve and continues to be symmetric about a vertical axis. Increase of the length of a crank is possible by the technique employed in shaper mechanisms[9].

The next best option is to increase the length of the ground link (*AD*). It is seen from Fig. 14 that increasing the length of *AD* results in coupler curves which are greater in height but lower in width compared to the original curve. *AD* being a ground link, it might be easier incorporate a linear actuator to vary the length of *AD* than it is for any of the other links. Increasing the length of *AD* by moving the ground pivot *D* horizontally was found to impart a small but undesirable tilt to the coupler curves of Fig. 14. An actuator which moves the ground pivot *D* in an arc about the initial position of *C* was seen to be better and these curves have been plotted in Fig. 14.

For the eight bar mechanisms shown in Figs. 6 and 7, a change in position of *D* needs to be accompanied by a corresponding and similar change in the positions of *F* (in Fig. 6) or J (in Fig. 7). These changes are easily effected using a single screw and will ensure that the change in coupler curve at *E* is replicated at *L*. There is no such convenient change point for the six bar mechanisms shown in Figs. 4 and 5. A change in the coupler curve at *E* is difficult to replicate at L in either of the six bar mechanisms because the lengths of the links associated with the cognates have to be changed. Thus, for a 1 DOF walking robot, the six bar mechanisms will be preferred while for introducing the capability of changing the gait by adding one more degree of freedom, it is necessary to adopt one of the eight bar mechanisms. One actuator would be responsible for walking and the other actuator would change the gait parameters.

3.2 Effect of change of gait parameters

It is essential to examine whether the motion of the coupler point is as desired once some link lengths are varied. The manner in which velocity, acceleration and jerk of the coupler point *E* changes as the lengths of *AB* and *AD* are increased, is shown in Figs. 16 to 21.

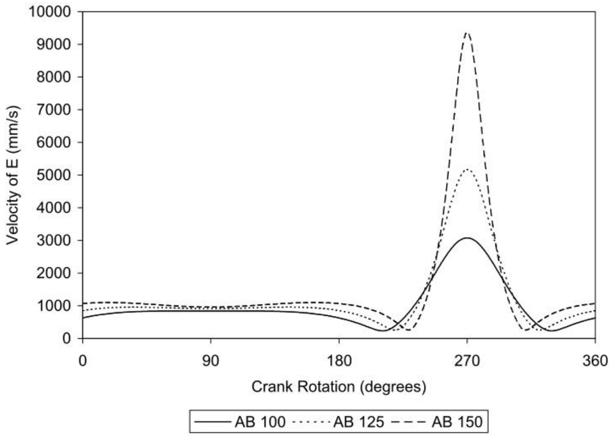

Fig. 16. Change in velocity of coupler point with increase in length of crank (*AB*)

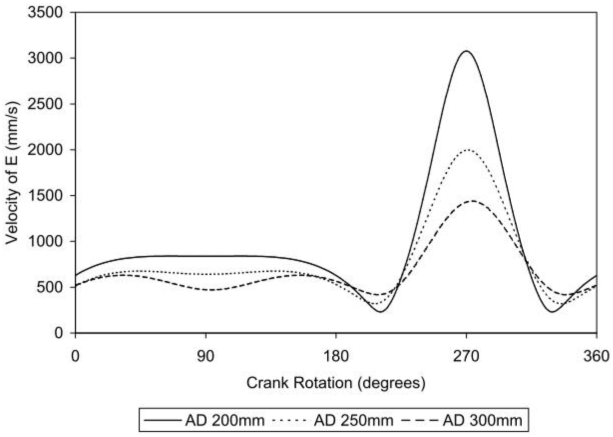

Fig. 17. Change in velocity of coupler point with increase in length of ground link (*AD*)

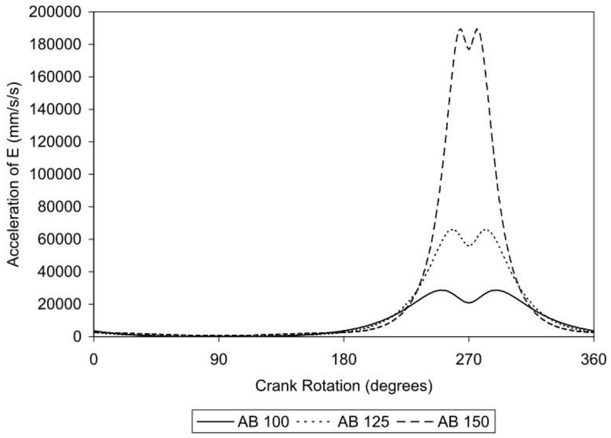

Fig. 18. Change in acceleration of coupler point with increase in length of crank (*AB*)

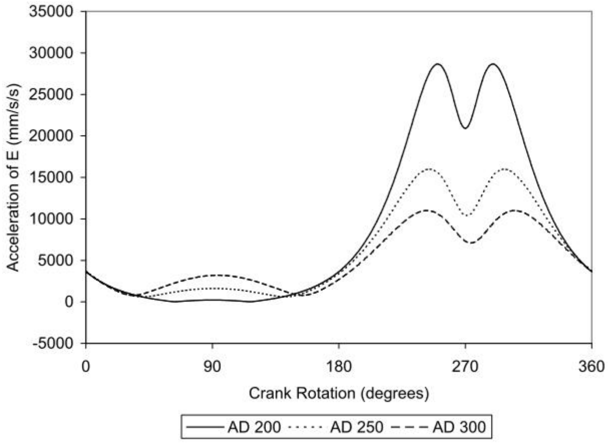

Fig. 19. Change in acceleration of coupler point with increase in length of ground link (*AD*)

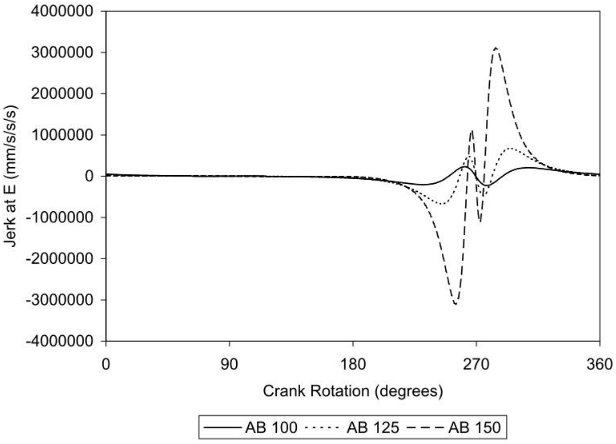

Fig. 20. Change in jerk of coupler point with increase in length of crank (*AB*)

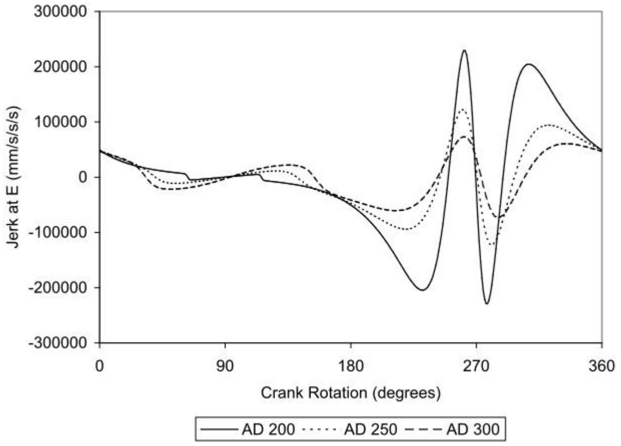

Fig. 21. Change in jerk of coupler point with increase in length of ground link (*AD*)

It is seen that the peak velocity, acceleration and jerk increase with increase in length of crank (*AB*) but decrease with increase in length of fixed link (*AD*). This apparently indicates a reason for choosing *AD* as the link length to be changed rather than *AB*. However, only the first halves of these plots—those corresponding to crank rotations between 0 and 180° (i.e. stance phases)—will be of relevance for the motion of the robot's body. A closer inspection of velocity, acceleration and jerk for this stance phase (Figs. 22 to 27) indicates the following:

(1) Peak velocity increases with increase in length of *AB* but decreases with increase in length of *AD*.

(2) Peak acceleration decreases with increase in length of *AB* and remains nearly constant with increase in length of *AD* (occurring at 0° of crank rotation).

(3) Peak jerk decreases with increase in length of *AB* and remains nearly constant with increase in length of *AD* (occurring at 0° of crank rotation).

However, the trends from the acceleration and jerk plots indicate that a further increase in length of *AD* will cause the peak acceleration and jerk to be higher and these peaks will occur at 90° of crank position. Thus, if ground link *AD* is chosen as the link whose length is to be changed for changing the gait and if acceleration of the robot's body turns out to be a limiting constraint, then the length of link *AD* should not be increased by more than 50%.

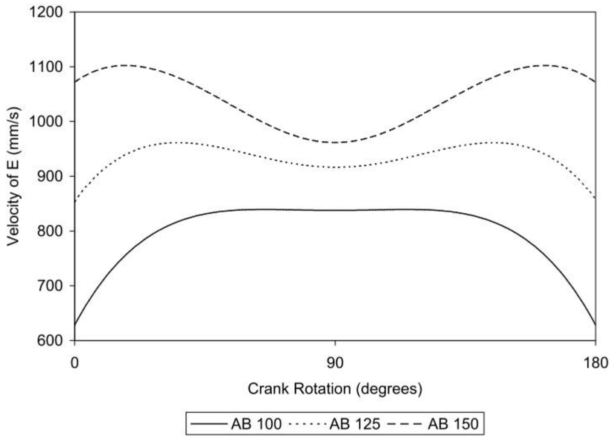

Fig. 22. Change in velocity of coupler point with increase in length of crank (*AB*) plotted for half of crank cycle

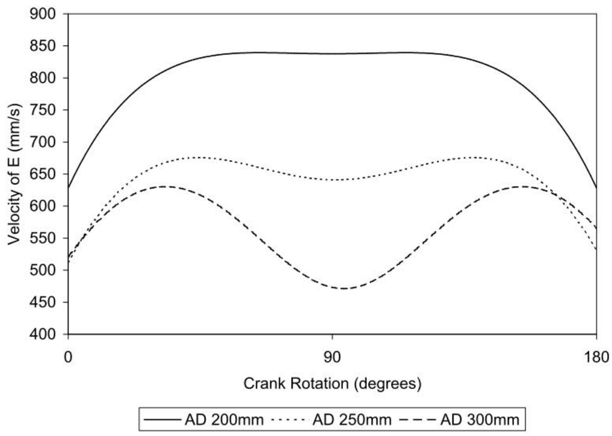

Fig. 23. Change in velocity of coupler point with increase in length of ground link (*AD*) plotted for half of crank cycle

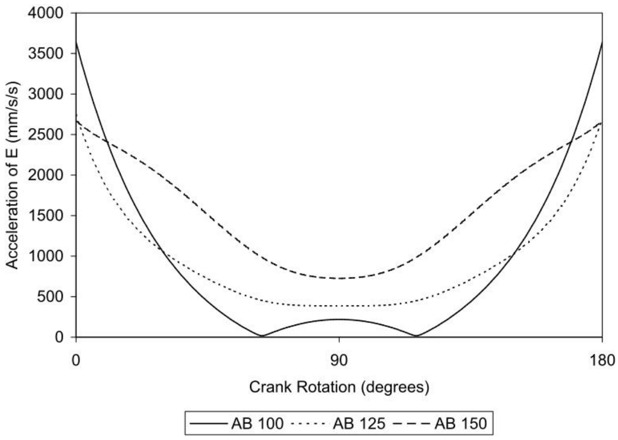

Fig. 24. Change in acceleration of coupler point with increase in length of crank (*AB*) plotted for half of crank cycle

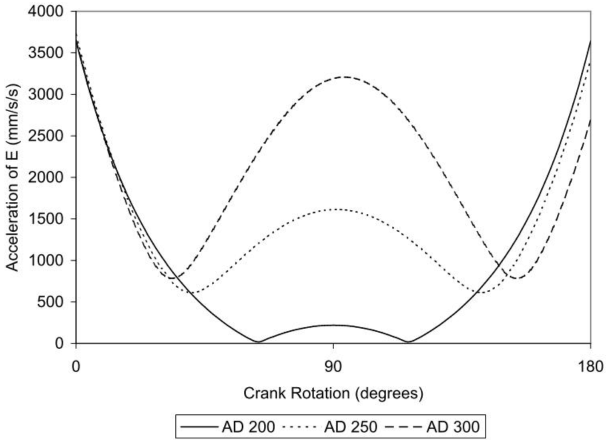

Fig. 25. Change in acceleration of coupler point with increase in length of ground link (*AD*) plotted for half of crank cycle

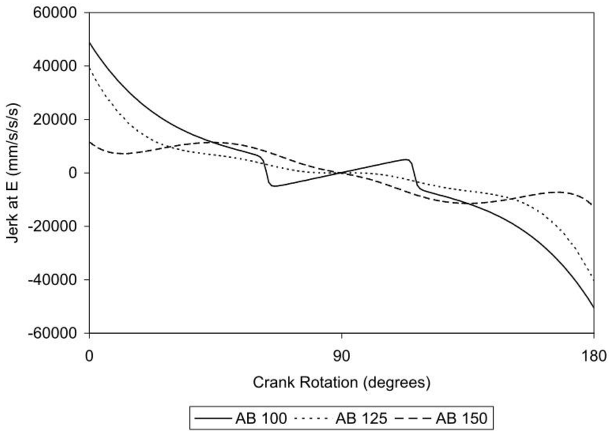

Fig. 26. Change in jerk of coupler point with increase in length of crank (*AB*) plotted for half of crank cycle

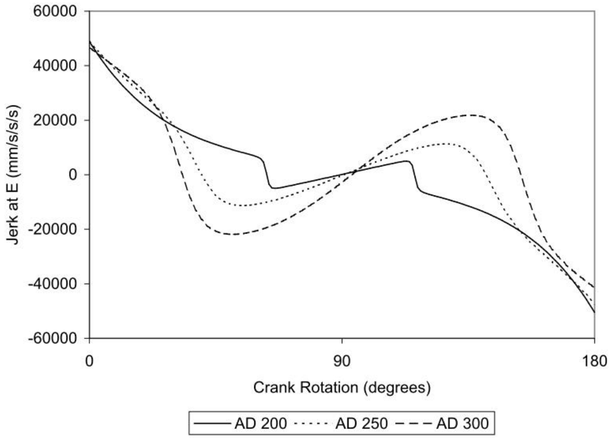

Fig. 27. Change in jerk of coupler point with increase in length of ground link (*AD*) plotted for half of crank cycle

To summarize, changing the gait by increasing the crank length (*AB*) will lead to the robot moving faster but experiencing lower peak acceleration and jerk. Changing the gait by increasing length of ground link *AD* will lead to the robot moving slower with negligible change in acceleration and jerk, provided the link length is not increased by more than 50%.

6 Conclusions

A study was undertaken to identify the four bar coupler curve best suited for designing the leg of a walking robot. The cognates of the Hoecken’s mechanism resulted in two six-bar mechanisms, both of which permit the coupler curve of Hoecken’s mechanisms to be shifted to a convenient position. Two eight-bar mechanisms were also designed which provide similar shifts. A robot could be designed to walk with only one actuator using the either the six bar or the eight bar linkages. A change of gait required for overcoming obstacles is possible by incorporating an additional actuator in the eight bar mechanisms. Analysis of variations in velocity, acceleration and jerk with the change in gait indicates that changing the length of either the crank or the ground link will provide the best motion.

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