Chapter 22
Design and Optimization of Foot Locus Trajectory of Theo Jansen Mechanism

N. Prashanth, S. Karthik, G. R. Rahul and T. B. Sandarsh

Abstract The single degree of freedom legged robots are functional in terms of its simplicity and performance on both even and uneven terrains. The performance stability of these legged robots is determined by the trajectory of their foot locus. In the present work, Theo Jansen mechanism is used as locomotive drive mechanism for legged robot. The mechanism is designed and optimized using the Synthesis and Analysis of Mechanism (SAM) software during the conceptual design phase. The embodiment design was completed using CATIA. Simplex and evolutionary algorithms were utilized for optimization of foot locus to improve its step height and stride length. The influence of the link length and the input crank angle on the foot locus trajectory has been illustrated and compared for three different trials. The obtained results are compared with standard foot locus. Further, the results derived in this work can be utilized in selecting the link length for Theo Jansen mechanisms for various applications.

Keywords Planar mechanisms · Theo Jansen · Optimization · Synthesis · SAM · CATIA · Legged robot

22.1 Introduction

The legged locomotive drive mechanism for robots are advantageous compared to that of wheeled drive mechanisms because of their all-terrain capability. Legged robots employ a mechanism which can be broadly characterized as multi degrees of freedom or single degree of freedom. Multi degrees of freedom legged robot have high manoeuvrability and they require complex control schemes with multiple gaits. Multi degrees of freedom legged robots are complex in mechanical design, expensive and often results in poor reliability [1]. Single degree of freedom legged mechanisms have several advantages to their credit because of its simplicity and

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low cost. Single degree of freedom legged mechanisms adopt planar mechanisms which are predictable and require simple control schemes. The inherent nature of planar mechanisms ensures that they do not suffer from redundant mobility. Due to these advantages, they are widely used in several applications. The performance of legged robots can be analysed using various metrics such as stability margin, energy efficiency and foot locus trajectory. For single degree of freedom legged robot, foot locus trajectory influences the robot's ability to overcome obstacles and also the energy efficiency of the mechanism [2]. Foot locus is the path traced by the leg in one cycle of crank. The trajectory with which the foot of a walking mechanism comes in direct contact with the ground is very important. As the crank rotates, the foot traces out a cyclical path. The foot locus of the leg is defined by mainly four phases; stride/drive, lift, return and lower phases.

Theo Jansen mechanism is a single degree of freedom mechanism which is widely used as locomotive drive mechanisms for legged robots. The Theo Jansen's linkage is a planar leg mechanism designed by the kinetic sculptor Theo Jansen to simulate a smooth walking motion. Jansen's linkage bears artistic as well as mechanical merit for its simulation of organic walking motion using a simple rotary input [3]. The foot locus of single degree of freedom legged robot should be optimized and the trajectory of the foot locus should be controlled for stable locomotion of the robot. The step height and stride length of legged locomotion determine the terrain in which the robot can move and efficiency of the robot locomotion [4]. In the present work, the optimization and the performance analysis of Theo Jansen mechanisms are studied using Synthesis and Analysis of Mechanisms (SAM) software. SAM was developed by Artas Engineering software. SAM is an interactive PC-software package for design, analysis (motion and force) and optimization of arbitrary planar mechanisms. Mechanisms can either be generated via the design wizards or they can be assembled from basic components including beams, sliders, gears, belts, springs, dampers and friction elements [5]. CATIA was employed to design the basic structures of the robot and planar mechanism. Digital mock-up (DMU) kinematic analysis on the designed mechanism was performed to check the interference of linkages and structures of the robot.

22.2 Optimization of Mechanism

Figure 22.1 shows the method adopted for analysis and design of Theo Jansen mechanism. The standard link lengths of the Theo Jansen mechanism are obtained from the 11 holy numbers given by Jansen [6]. It is scaled down to the link lengths to our requirement by taking the ratios of the 11 holy numbers. The scaled link lengths were then utilized to construct the Theo Jansen mechanism in SAM and the corresponding foot locus was obtained. Table 22.1 shows the link lengths and the foot locus traced by the standard Theo Jansen mechanism. From the standard foot locus, optimization was performed based on the foot locus requirement for uneven terrains. The parameter of the foot locus is shown in Fig. 22.2.

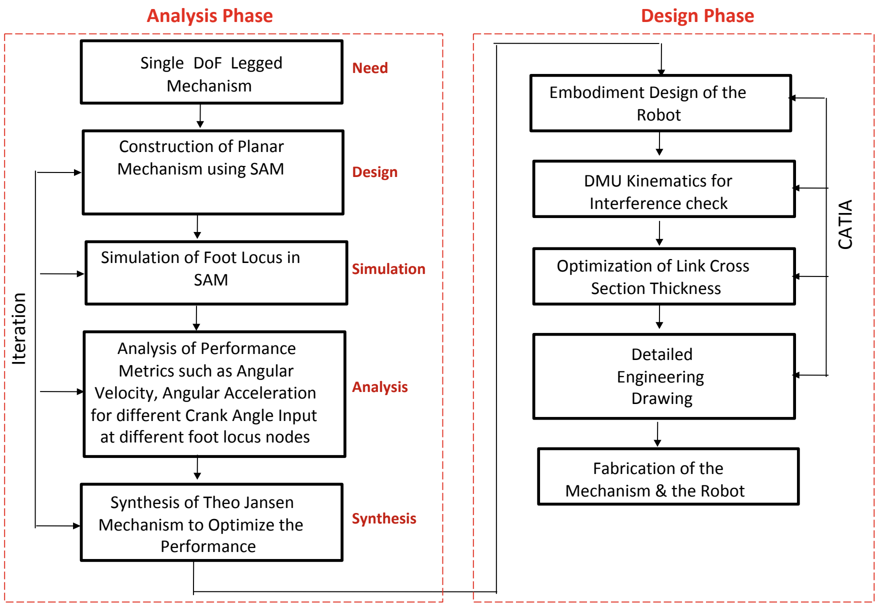
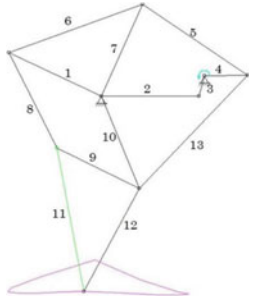


Fig. 22.1 Methodology

Table 22.1 Standard link length and foot locus of Theo Jansen mechanism

Links	Standard link length (mm)	Standard foot locus result (mm)
1	60.108	Step height: 23.074 mm
2	57.812	Stride length: 114.254 mm
3	12	
4	23.840	
5	78.698	
6	88.691	
7	63.281	
8	56.723	
9	56.143	
10	60.455	
11	101.825	
12	83.304	
13	93.595	

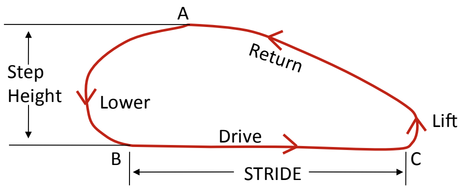


Fig. 22.2 Foot locus parameter [4]

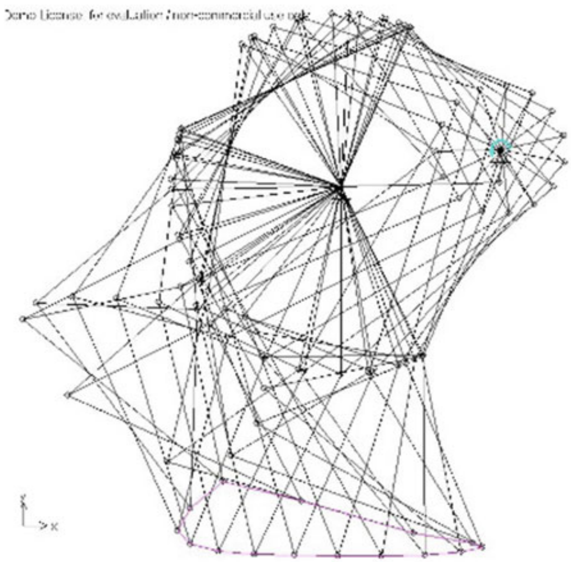


Fig. 22.3 Hodograph of Theo Jansen mechanism obtained from SAM

The hodograph obtained of Theo Jansen mechanism for one complete cycle is shown in Fig. 22.3.

The optimization of standard foot locus trajectory was performed by the following steps.

- **Modelling of Linkage Mechanism**: Standard Theo Jansen mechanism was constructed in SAM using the beam elements.
- **Configuring the Inputs (Actuators) and Constraints**: The input motion is given to the crank for the rotation of the crank.
- **Tracing Standard Foot Locus**: The standard foot loci for the standard link lengths were obtained. The coordinates of the standard foot locus were obtained.
- **Creating the Optimized Foot Locus Coordinates**: Based on the standard foot locus coordinates, a set of new target coordinates were derived to optimize the step height and stride length.
- **Input Target Coordinate for Synthesis of Links**: The coordinates for target path were selected in the software.
- **Define the Reference Frames**: The fixed supports of the mechanism are selected in the optimization process.

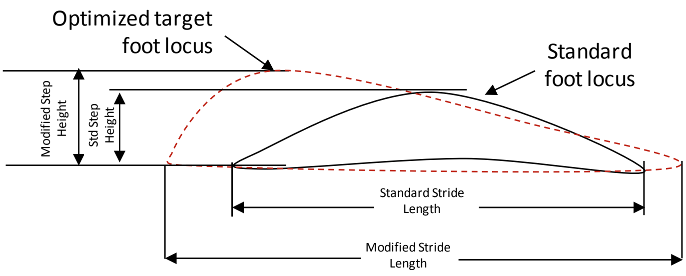


Fig. 22.4 Standard and optimized foot locus

- **Select the Optimization Algorithm**: In the optimization, one can choose between user-controlled modus and automatic modus. In the user-controlled mode, a global exploration of the parameter space is performed based on evolutionary algorithms leading to a set of solutions. The user can then select any of these solutions and further refine it via a local optimization, which can be either based on an evolutionary approach or on a simplex method. In the automatic mode, the best solution of the global search is automatically refined in a local optimization (again, either based on an evolutionary or a simplex approach). In the present work, the automatic modus is chosen as it gives the best solution.
- **Optimize**: After defining all the inputs, the optimization process is commenced; the software performs multiple iterations to obtain the target foot locus path obtained as shown in Fig. 22.4. During the process of optimization, the software will automatically synthesize the link length to obtain the desired foot locus.
- **Tabulation of New Link Lengths**: Once the desired foot locus was obtained through optimization, the updated link lengths were tabulated for CAD modelling.

As shown in Fig. 22.4, the target coordinates were entered as the reference file for the optimization process. The thick lines represent the standard foot locus and the dotted line represents the optimized foot locus. Using the above foot locus, several other foot loci were obtained by changing the link lengths to achieve longer stride length and higher step height.

Figure 22.5 shows the comparison of three different foot loci with that of the standard. First, the stride length and step height were compared with the standard foot locus and all the linkages. Percentage of increase or decrease of the link length was computed to identify the links which influenced the foot locus the most. These results were further tabulated as shown in Table 22.2. In the first trial, the stride length and step height are increased by 2.03% and 35.05%, respectively. This foot locus has higher step height and longer stride length when compared to all other trials; however, the main problem associated with this foot locus is the mechanism suffers from interference between the links during motion, the reason for interference is the increase in link length leading to higher step height, in order to overcome this problem, the cross-section thickness of link should be very small, however, reduction in cross-section thickness will further lead to poor leg strength, therefore, trial-1 was

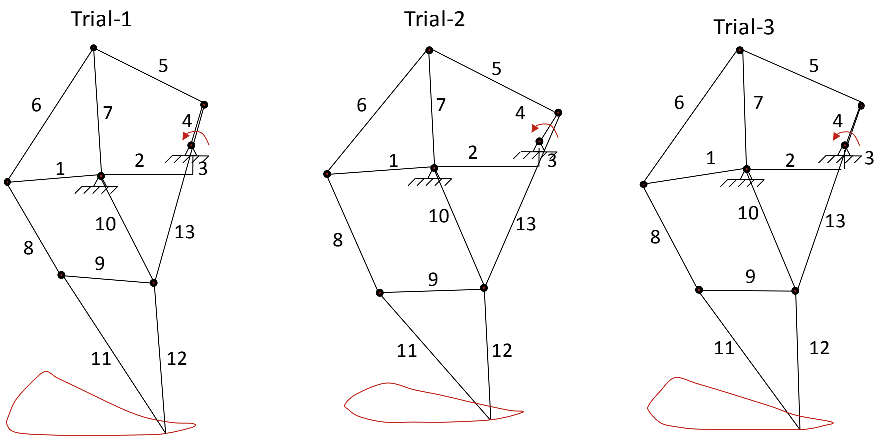


Fig. 22.5 Various foot loci in comparison with standard foot locus

Table 22.2 Nodes identified for the comparison of Theo Jansen foot locus

Link No.	Standard link length (mm)	Trial-1		Trial-2		Trial-3	
		Link length (mm)	% of change in link length (%)	Link length (mm)	% of change in link length (%)	Link length (mm)	% of change in link length (%)
1	60.108	60.108	0.00	60.32	0.35	61.832	2.87
2	57.812	57.812	0.00	57.812	0.00	57.812	0.00
3	12	12	0.00	12	0.00	12.12	1.00
4	23.84	25.153	5.51	20.96	−12.08	23.408	−1.81
5	78.698	72.952	−7.30	80.273	2.00	78.698	0.00
6	88.691	88.691	0.00	87.96	−0.82	91.419	3.08
7	63.281	63.281	0.00	63.281	0.00	63.281	0.00
8	56.723	58.317	2.81	69.57	22.65	64.089	12.99
9	56.143	56.679	0.95	58.8	4.73	58.601	4.38
10	60.455	63.01	4.23	71.57	18.39	68.92	14.00
11	101.825	102.1	0.27	91.813	−9.83	93.677	−8.00
12	83.304	76.1	−8.65	68.965	−17.21	72.902	−12.49
13	93.595	90.623	−3.18	105.627	12.86	103.7	10.80
Stride length	114.254	116.574	2.03	95.5	−16.41	102.6	−10.20
Step height	23.074	31.163	35.06	20.492	−11.19	27	17.01

not considered for further analysis. In the second trial, the stride length and step height were decreased to 16.41% and 11.19%, respectively. This type of foot locus will be more suitable for even terrains, since its step height is less compared to all other foot loci, and hence, this locus was not further considered for analysis. In the third trial, there is an increase in the step height by 17.01% which is suitable to overcome the obstacles of up to 27 mm and there is a decrease in the stride length by 10.2%. Due to the increased step height, it is inferred that foot locus obtained in trial-3 is suitable for both even and uneven terrains. From the above results, the foot locus obtained during trial-3 was chosen as the optimal and it was further considered for embodiment design.

22.3 Design of Legged Robot

Theo Jansen mechanism was designed using 3D CAD software CATIA V5. The legs of the robot were modelled using the link lengths obtained from SAM software. These links were then assembled to form the leg mechanism. Total of eight Theo Jansen mechanisms was modelled. The chassis for the robot was designed using sheet metal workbench. Pair of each leg was actuated by one geared DC servo motor, and gear drives were used to transmit power to the legs of the robot. Figure 22.6 shows the assembly of the legged robot.

To ascertain the interference between links and chassis in the robot, digital mock-up (DMU) kinematics analysis was performed in CATIA. Any interference in the

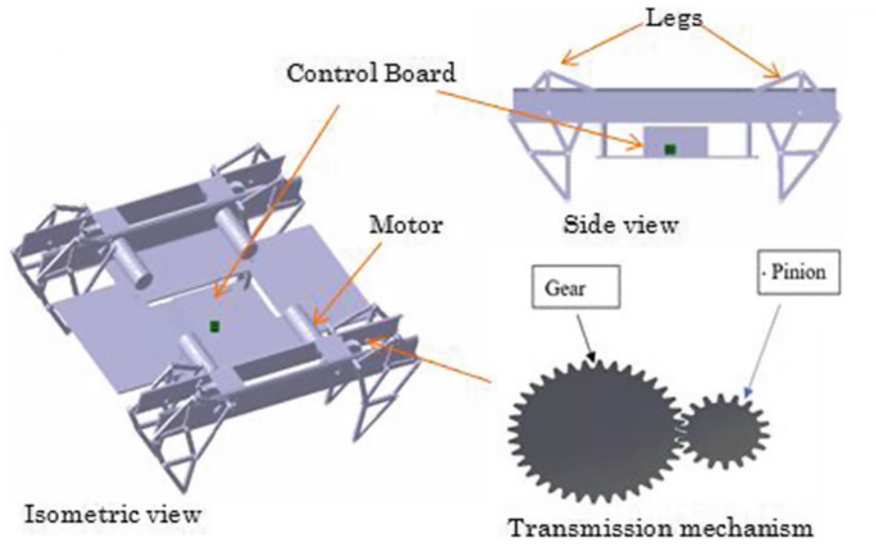


Fig. 22.6 Assembly of the legged robot

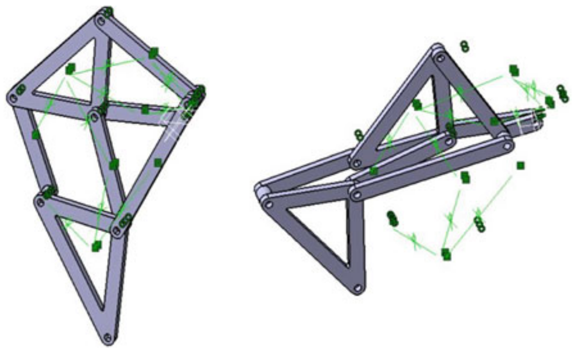


Fig. 22.7 Interference check in CATIA

individual link lengths was overcome by optimizing the thickness of the links and also by creating the required stand-off distances between the links (Fig. 22.7).

22.4 Performance Analysis

In this section, the standard foot locus is compared with that of the three different loci obtained during optimization. The foot locus trajectory of Theo Jansen mechanisms is unique for each trial, and hence, they cannot be compared in terms of its path alone; therefore, critical nodes were identified along the foot locus which is common. These nodes are shown in Fig. 22.8.

Table 22.3 shows the influence of identified nodes on the foot locus generated by the Theo Jansen mechanism.

Table 22.4 shows the angular velocity and angular acceleration of the standard Theo Jansen robot leg (link which makes contact with the ground) as the crank rotates. Tables 22.5, 22.6 and 22.7 show the crank angle versus angular velocity and angular acceleration of the robot leg (link which makes contact with the ground) for the three trials, respectively. The analysis of angular acceleration of leg plays an important role, since the acceleration and frictional forces have interaction during

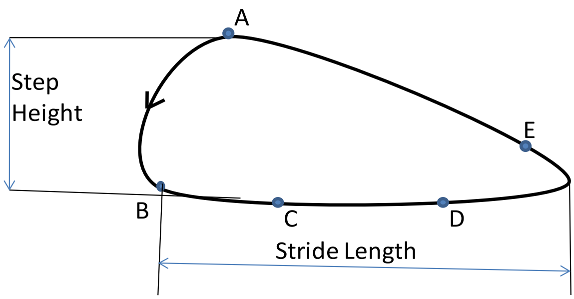


Fig. 22.8 Major points affecting the foot locus

Table 22.3 Influence of nodes identified for the comparison of Theo Jansen foot locus

Nodes	Influence on mechanism
A	Step height determines the ability to overcome obstacles
B	Touchdown determines the point of contact with ground
C and D	Determines the stability during the stride length
E	Post lift-off retardation and approach towards maximum step height

Table 22.4 Performance parameters of Theo Jansen mechanism for standard link lengths

Nodes	Crank angle (rad)	Angular velocity (rad/s)	Angular acceleration (rad/s^2)
A	3.362	−4.696	−151
B	5.037	1.003	15.41
C	5.875	0.6952	11.6
D	6.713	2.194	9.959
E	4.2	−4.132	−35.16

Table 22.5 Performance parameters of Theo Jansen mechanism for trial-1

Nodes	Crank angle (rad)	Angular velocity (rad/s)	Angular acceleration (rad/s^2)
A	3.382	−2.09	−69.662
B	5.128	0.347	2.776
C	5.996	0.348	2.927
D	7.252	1.56	1.055
E	2.693	0.08	−10.114

Table 22.6 Performance parameters of Theo Jansen mechanism for trial-2

Nodes	Crank angle (rad)	Angular velocity (rad/s)	Angular acceleration (rad/s^2)
A	3.492	−3.771	−15.32
B	5.06	0.769	13.617
C	5.972	0.865	9.613
D	6.951	2.116	5.919
E	3.07	−1.856	−37.78

Table 22.7 Performance parameters of Theo Jansen mechanism for trial-3

Nodes	Crank angle (rad)	Angular velocity (rad/s)	Angular acceleration (rad/s^2)
A	3.58	−2.621	−64.04
B	4.837	1.363	15.63
C	5.675	0.380	10.96
D	6.512	1.773	10.6
E	3.161	−4.937	−98.36

the locomotion of the robot, and hence, it is imperative to understand the magnitude and directions of various parameters such as velocity and acceleration [7–9].

Figures 22.9 and 22.10 represent the crank angle versus angular velocity and crank angle versus angular acceleration, respectively, for the optimized foot locus, i.e. for trial-3. From the above graphs, one can observe that there is a rapid change in velocity from node A to B and Node D to E resulting in change of acceleration. The velocity from point B to D is almost uniform and therefore it results in minimum acceleration. The rapid change in velocity and acceleration happens during the lift and lower phase.

Figure 22.11 shows the comparison of angular acceleration between the standard Theo Jansen mechanism and the optimized foot loci. It can be observed that between nodes B, C and D, the variation of angular acceleration across the standard foot locus and optimized foot loci is negligible. However, at nodes A and E, the angular acceleration varies across all the foot loci. In the standard foot locus, at node A, the leg experiences maximum acceleration and its acceleration reduces as its approach

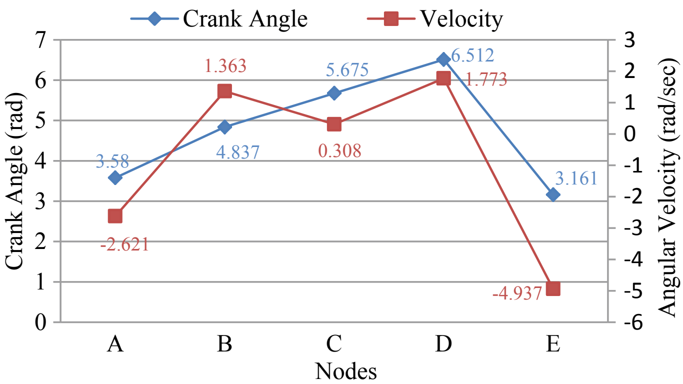


Fig. 22.9 Trial-3 crank angle versus angular velocity

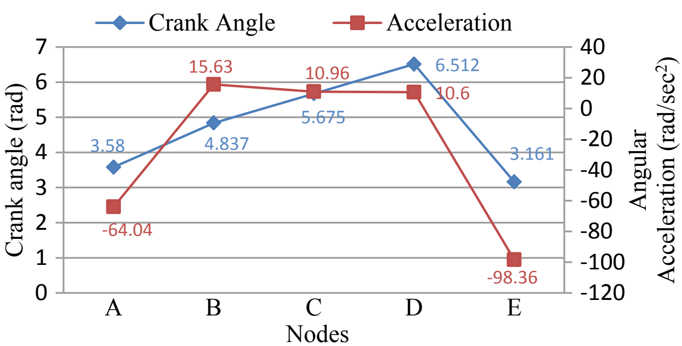


Fig. 22.10 Trial-3 crank angle versus angular acceleration

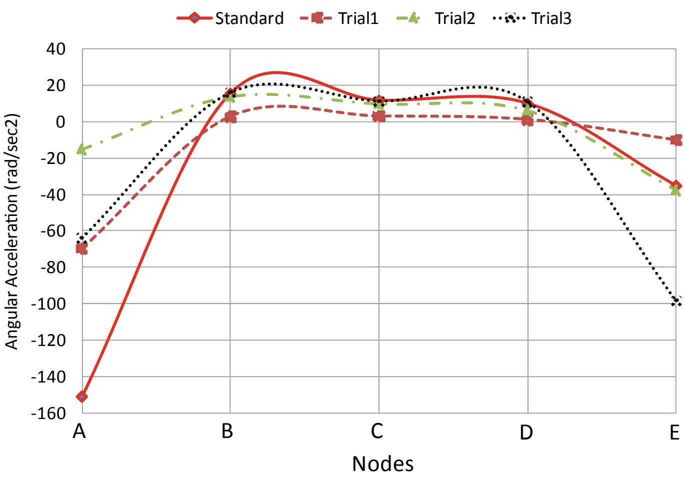


Fig. 22.11 Comparison of angular acceleration between standard and optimized foot loci

towards node B. In trial-3, it can be observed that the difference between angular acceleration between nodes A and E is considerably less than the standard foot locus.

22.5 Conclusions

While comparing the standard foot locus with that of the optimized foot loci, one can observe that in the standard link the maximum step height is achieved at the centre of the stride length, and hence, when the leg approaches the lower phase, it would not overcome the obstacle. In the optimized foot locus, the maximum step height is achieved during the lower phase and such foot loci are suitable for uneven terrains or overcome obstacle (obstacle size based on step height). Hence, it can be used in several applications. The results obtained in the present work can be further utilized to incorporate Theo Jansen mechanism for various applications. Further, the optimized mechanism will be fabricated and integrated with the robot to test its performance under real-world conditions such as different terrain, gaits and phase angles.

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