Influence of Link Lengths & Input Angles on the Foot Locus Trajectory of Klann Mechanism

N Prashanth¹*, R M Manoj², B Nikhil²
¹Research Scholar, Department of Mechanical Engineering,
²Under Graduate Scholars, Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Bengaluru, INDIA.

E-mail: prashanth.n@nmit.ac.in

Abstract. Locomotive drive mechanisms for robots have been an active research area in the field of mobile robotics. Several drive mechanisms such as wheeled, legged, hybrid & reconfigurable mechanisms have been extensively studied. The legged locomotive drive mechanism has several advantages to its credit & it is often bio-inspired. The disadvantage of legged locomotive drive mechanism in general is it is often considered as complex in design due to its multi degrees of freedom which requires complex control scheme. This has led roboticists to explore minimal legged locomotive drive mechanisms consisting of single degrees of freedom. The present work focuses on synthesis and analysis of one such planar mechanism such as klann mechanism for a mobile robot application. In this work, we have synthesized the various linkages of klann mechanism to find the optimal foot locus trajectory. The synthesis and analysis of mechanism is performed using SAM (Synthesis and analysis of mechanism) software. We have described influence of various parameters such as position, velocity and acceleration on the foot locus. We have compared the foot locus for three different foot locus by performing the kinematic analysis. Various parameters such as position, velocity and acceleration of linkages are compared & illustrated in detail. The information provided in this work will help the roboticists to select appropriate link length for klann mechanism to obtain various foot locus designs. This information may be further used to design efficient legged locomotive drive mechanisms for various terrain conditions.

1. Introduction

The legged locomotive drive mechanisms has been extensively studied in the field of mobile robotics, legged mobile robots(LMR) are advantageous compared to wheeled mobile robots(WMR) has it can be used in all terrain conditions [1]. The legged robots are broadly classified based on the degrees of freedom (DoF) it possesses. There are multi-degrees of freedom legged robot and single degrees of freedom legged robot. The multi degrees of freedom legged robots require more actuators for the motion and its complexity is more in terms of mechanical design and control scheme. Hence single degrees of freedom legged robots play an important role [2]. There are many single degrees of freedom legged robots based on several planar mechanisms, the most popular amongst them are Klann mechanism and Theo Jansen mechanism. The stability of legged locomotion determines the terrain in which the robot can move and efficiency of the robot locomotion. [3]. In the present work the focus is on synthesis and analysis of foot locus trajectory using Klann mechanism. Klann mechanism is the single degrees of freedom mechanism which is widely used as locomotive drive mechanisms for legged robots [4]. The linkage consists of a frame, a crank, two grounded rockers, and two couplers all connected by pivot joints [5]. As shown in figure 1. The stability of Robot is determined by the foot locus traced by the leg of the robot. The foot locus is the path traced by the leg of the robot for one cycle [6]. The optimisation and the Performance analysis of the mechanisms is performed in software called SAM (Synthesis and Analysis of Mechanisms). SAM was developed by Artas Engineering software’s. 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 [7].
2. Optimization Technique

Step Height & Stride Length are the two important parameters of the foot locus which are considered for optimization. Step height determines the lift of the leg along vertical axis while the stride length determines the horizontal distance covered by each leg for one complete revolution of the crank [8]. From the performance point of view, higher the step height better will be the all-terrain capability, while longer stride length will help in faster displacement of the robot. In the present work, since klann mechanism is non-reconfigurable and has fixed link length, the step height & stride length will also be fixed. The step height & stride length of mechanism can be varied by changing the input crank angle ($\theta_{in}$) and link lengths($l_n$) during synthesis stage with a limiting factor without compromising on the validity of the mechanism. Therefore, the objective function for the optimization of mechanism is maximizing the co-ordinates of step height ($x_{sh}, y_{sh}$) & stride length ($x_{sl}, y_{sl}$).

$$\text{Max}(x_{sh}, y_{sh}, x_{sl}, y_{sl}) = f(\theta_{in}, l_1, l_2, l_3 \ldots l_n)$$  \hspace{1cm} (1)

The optimization process in SAM involves two step processes: 1. Exploration of the design space 2. Optimization of a specific solution. To begin with the entire parameter space of the mechanism is explored using a combination of pure Monte Carlo technique & evolutionary algorithm, which is derived from genetic algorithm. Further local optimization is performed using simplex technique. The target co-ordinates of the foot loci are specified by the designer along with the boundary conditions of the mechanism (constraints only). The combination of a global exploration strategy and a local optimization strategy with the designer in the loop for selecting the mechanism that is further optimized is believed to give the best trade-off between speed and coverage of the design space.

The SAM provides basic GUI required optimizing planar mechanisms. Following steps were followed for complete optimization of both mechanisms [9].

Step 1: Defining the Objective Type- The objective type which we chose was path specified in terms of nodes of the foot loci which covered both the peak node for stride height & stride length.

Step 2: Definition of the element/node property to be optimized

Step 3: Target Definition-The co-ordinates of the nodes for the required foot locus was defined using ASCII based file format. i.e.

$$\begin{align*}
X_1 & \quad Y_1 \\
X_2 & \quad Y_2 \\
\vdots & \quad \vdots \\
X_n & \quad Y_n
\end{align*}$$

Step 4: Specifying the Objective Performance Number: Maximum was chosen as the objective performance (other options include: absolute maximum, average, RMS, standard deviation)

Step 5: Optimization Target was specified to be maximum

Step 6: Further the parameter space of the mechanism was chosen. Parameter space represents the properties of the nodes which can be varied during the optimization.
3. **Optimization Results**

The Klann mechanism was optimized for different types of foot locus depending on the varying parameters such as stride length and step height, the variation in the parameters results in different foot loci with varying dimensions of the klann mechanism[10]. In the present work, we compared the foot locus trajectory of standard foot locus with the maximum & optimized foot locus trajectory. Iteration 1 results in foot locus with maximum stride length & step height. Iteration 2 represents the standard foot locus, while iteration 3 results in optimized foot locus. The dimensions of links length for maximum, standard and optimised foot locus is shown is shown Table 1. Figure 2 shows the corresponding foot locus obtained for Iteration 1, 2 & 3 respectively.

**Table 1** Link Length & Foot Locus Parameters of Klann Mechanism.

| Links | ITERATION 1 Link Lengths (mm) For MAXIMUM Stride Length & Step Height | ITERATION 2 Link Lengths (mm) For STANDARD Stride Length & Step Height | ITERATION 3 Link Lengths (mm) For OPTIMIZED Stride Length & Step Height |
|-------|------------------------------------------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------------------|
| 1     | 150.29                                                                  | 123.304                                                                | 150.290                                                                |
| 2     | 99.49                                                                   | 87.794                                                                | 99.49                                                                 |
| 3     | 240.958                                                                 | 209.557                                                                | 240.940                                                                |
| 4     | 55.26                                                                   | 48.814                                                                | 55.268                                                                |
| 5     | 56.373                                                                  | 37.568                                                                | 56.373                                                                |
| 6     | 96.895                                                                  | 99.5243                                                               | 102.89                                                                 |
| 7     | 151.415                                                                 | 135.533                                                               | 159.39                                                                |
| 8     | 49.202                                                                  | 44.838                                                                | 49.202                                                                |
| 9     | 37.850                                                                  | 21.704                                                                | 32.842                                                                |

**Result**

- Step Height = 53.18mm
- Step Height = 26.529mm
- Step Height = 45.094mm
- Stride Length = 168.57mm
- Stride Length = 63.394mm
- Stride Length = 137.137mm

Figure 2 (a) (b) (c) Foot Loci obtained using SAM for Iterations 1, 2 & 3 respectively

4. **Performance Analysis**

The Performance analysis of the Klann mechanism is obtained by marking ideal nodes on the foot locus shown in Figure 3 and obtaining the velocity and acceleration values on that nodes.

Figure 3 Major Points affecting the foot locus
Table 2: Nodes Identified for the comparison of Klann & Theo Jansen Foot Locus.

| Nodes | Influence on Mechanism |
|-------|------------------------|
| A     | Step Height - Determines Ability to overcome Obstacles |
| B     | Touchdown - Determines Point of contact with ground |
| C & D | Determines the Stability during the strike length |
| E     | Post Lift-off - Retardation from point D & approaches towards point A |

The results of variation in the velocity and acceleration versus the crank angle are shown in the table 3.

Table 3: Performance Parameters of Klann mechanism for maximum stride length and step height

| Nodes | ITERATION 1-MAXIMUM | ITERATION 2-STANDARD | ITERATION 3-OPTIMIZED |
|-------|----------------------|-----------------------|------------------------|
|       | Crank Angle (rad)    | Velocity (rad/sec)    | Acceleration (rad/sec²) |
| A     | 1.141                | 0.403                 | 23.547                 |
| B     | 0.127                | -0.711                | 11.522                 |
| C     | 5.236                | -1.578                | 3.224                  |
| D     | 4.174                | -2.325                | -0.315                 |
| E     | 2.852                | 1.946                 | -24.528                |
|       | 1.679                | 0.726                 | 6.614                  |
|       | 0.131                | -0.417                | 2.887                  |
|       | 5.415                | -0.666                | 1.028                  |
|       | 4.723                | -0.715                | -0.117                 |
|       | 2.486                | 1.101                 | -2.327                 |
|       | 1.77                  | 0.604                 | 13.779                 |
|       | 0.2064               | -0.322                | 2.792                  |
|       | 5.958                | -1.032                | 3.460                  |
|       | 4.239                | -1.204                | -2.003                 |
|       | 2.822                | 1.119                 | -14.096                |

5. Kinematic Analysis

The kinematic analysis of the klann mechanism was performed using SAM and CATIA software. SAM was used to obtain velocity & acceleration of leg tracing the foot locus, while CATIA was used to model the optimized klann mechanism and check for any interference between the links. The interference check was performed using DMU (Digital Mock-up) workbench. Further, for the optimized klann mechanism, a foot locus was obtained in CATIA software to validate the foot locus obtained in SAM. It was observed that the foot locus obtained in CATIA was same as that obtained in SAM which is shown in the Figure 4.

Figure 4: (a) CATIA model of klann mechanism, (b) Foot Locus traced by Klann mechanism in CATIA DMU kinematics respectively

6. Modelling and Fabrication

The optimised foot locus was modelled in CATIA software after the interference check and then the mechanisms were fabricated and assembled to the chassis. The Chassis was modelled using Sheet Metal Workbench. The CATIA model of the assembled robot and fabricated robot is shown in the Figure 5.

Figure 5: (a) CATIA assembly model, (b) fabricated assembly respectively
7. Results and Discussions

The performance parameter such as angular velocity and angular acceleration of the Klann mechanism leg (link which makes contact with the ground) for three different foot locus i.e. maximum, standard and optimum stride length and step height is shown in the subsequent plots. Figure 6 shows the variation of angular velocity of the leg for iteration 1. The angular velocity is increasing as leg approaches from node A to D; here negative sign indicates change in direction of velocity vector. Figure 7 shows the variation of angular acceleration which increases while lifting the leg and it gradually decreases on the nodes B, C and D. Figure 8 shows the slope of angular velocity for iteration 2, angular velocity between nodes B, C and D is less compared to that of iteration 1. In Figure 9 the plots of node vs crank angle and acceleration is shown which infers that the magnitude of angular acceleration is less compared to that of iteration 1.

Figure 6. Node v/s Crank Angle & Velocity

Figure 7. Node v/s Crank Angle & Acceleration

Figure 8. Node v/s Crank Angle & Velocity

Figure 9. Node v/s Crank Angle & Acceleration

Figure 10. Node v/s Crank Angle & Velocity

Figure 11. Node v/s Crank Angle & Acceleration
In iteration 3, the plots of node vs crank angle and velocity is shown in Figure 10 which infers that magnitude of angular velocity doesn’t vary much between nodes C, D and E. In Figure 11, the plots of node vs crank angle and acceleration is shown which infers that the acceleration doesn’t vary much between nodes B, C and D & acceleration between nodes A & E is almost same in magnitude, due to this phenomenon, there will be smooth transition in the acceleration from the upper phase of the foot locus to lower phase, as a result, the foot locus obtained under iteration 3 is considered as optimal. Further it has to be noted that the velocity & acceleration of links has significant influence on the interaction of robot leg with the ground. Since the frictional forces are greatly influenced by the acceleration of a body, leg making contact with the ground at very high acceleration should be avoided as it leads to slippage while walking.

8. Conclusions

The optimization of the Klann mechanism is performed for three different iterations of three different foot locus trajectory. The different foot locus helps in various applications where the foot locus with the higher step height is used in avoiding obstacles and foot locus with higher stride length helps in stability over the continuous locomotion of the robot. The results in this paper help in identifying the dimensions of the Klann mechanism which can be used for different robot locomotive application. Further, the fabrication of the legged robot which utilizes the Klann mechanism has been completed and control system will be integrated with the robot & its performance analysis on different terrain will be tested.

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