Effect of Variation of Link Lengths on the Stability of Klann Mechanism for a Quadruped Robot

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Abstract - *Legged robots and wheeled robots are well known for their ability to usher various terrains. The caliber of wheeled robots fall down as the terrain is subjected to irregularities. An alternative to this is the implementation of legged robots for these kinds of terrains. Robots with single degree of freedom can be focused due to its control ability schemes in rough terrains. This purpose can be achieved with the help of bipeds, quadrupeds, hexapods etc. Each of these robots are run in a particular gait pattern. In this paper we examine a way to select linkage parameters for the leg of a quadruped robot. By the variation of different link lengths, different possibilities of trajectories are explored. Motivated by the recent developments in legged robots and biology, we also examine the method to control the movement of the single degree of freedom leg. Reduction in the impact forces on the legs by the addition of an external spring is achieved.*

Key Words: Quadruped, Klann Mechanism, Link lengths, Gait pattern, Impact forces.

1. INTRODUCTION

Legged locomotion in robots finds numerous applications in the fields such as surveillance, material transport, industrial inspection, rescue mission and navigation [1, 2]. Legged motion is an extension of a wheel to form a rimless wheel, eventually a biped. Bipeds, Quadrupeds and Hexapods are few types of legged motion configurations. Mainly inspired by legged animals, these robots can perform activities such as walking running, jumping, hopping etc. depending on the task. These are designed to explore various kinds of terrains. The main challenge is to achieve the desired motion by controlling the motion kinematics. Continuous research is being done by Boston Dynamics Lab for the various Quadruped demonstrations involving Spot, SpotMini, Rhex and Sandflea [12]. All these types can be modelled and controlled in many ways namely by Kinematic Links, Pneumatic cylinders and Direct drives. Each one has their own advantages and disadvantages. Several researchers emphasize the importance of gait generation in controlling any kind of legged motion. The commonly used techniques involve Reinforcement Learning [3], Fuzzy Logic [4], Graph Search and many more. Several recent studies examined dynamics-based torque controls using torque controlled quadrupeds [5]. Using a Single DOF reconfigurable planar mechanism [6], the authors present a method to generate input trajectory for reconfigurable quadrupeds. Also with [7], the authors present an approach to generate the required trajectory by the variation in link angles.

The selection of kinematic linkages for any legged motion configuration depends on Degrees of Freedom (DOF) of the mechanism. Lesser the DOF, easier it is to control. Many mechanism such as Dunshee Mechanism, Chebyshev Mechanism, Theo Jansen Mechanism, Klann Mechanism and Stephenson Mechanism are available to achieve the desired motion of the Leg configurations [8, 9]. In this paper, we have considered Klann Mechanism which consists of six links and a single DOF, for further study. Klann Linkage named after Joe Klann, was developed in 1994. It is an extension of Stephenson type III configured mechanism. The main challenge associated with a Klann mechanism is the generation of the output trajectories based on different terrains and the control problem. In this paper, we present a method to select the optimum link lengths of the mechanism and to configure a stable gait pattern.

2. Approach

The knowledge of the coordination of links of a quadruped for gait transition is essential for understanding the locomotive mechanism of any legged robot. The commonly observed gait transitions in legged animals are Walk, Trot, Bound and Gallop. The synchronization of all these transitions should be considered for designing flexible and efficient locomotion. The representation of different legs in a quadruped robot is shown in Fig.1. Each leg of the quadruped is represented through Klann mechanism having a single Degree of Freedom (DOF). The phase coordination among the adjacent legs generates various trajectories. Several attempts are made in the generation of trajectories by changing the link angles in the Klann mechanism. In this paper we studied the variations of gait transition patterns by altering the link lengths while keeping link angles constant. Further, different configurations of leg movements are specified for stability analysis and motion generation. It is observed that, the input and transition angle of the crank enables in the shifting property of the leg. Based on the required configuration, the different combinations were studied. It is also attempted to avoid the impact on the leg during motion, by endorsing the leg with a spring.

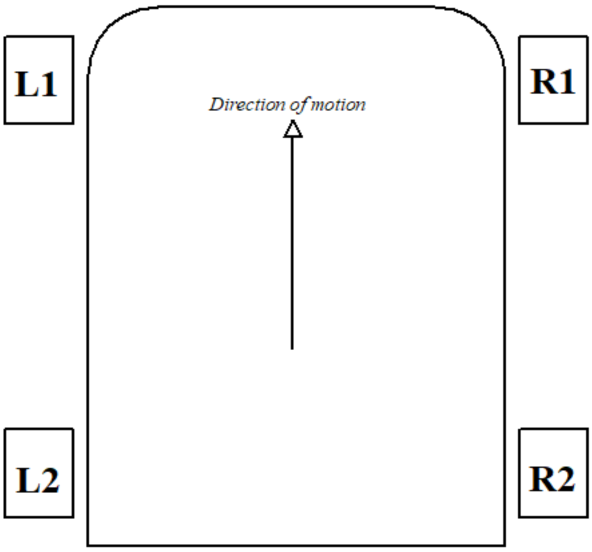


Fig.1.Representation of legs in a quadruped

The Phase relationship [10] of locomotion patterns is shown in Table.1. It can be observed that in walk and gallop pattern, there is a 90 degree shift among the four legs. In case of trot and bound the angle shifting takes place in 180 degree interval. However, the pattern in the all the four gait transitions is different. In the above transitions, the phases L1, R1, L2, R2 shifts periodically. In every cycle of the crank the set of legs are termed as 'Support' (refers to the leg in contact with the ground) and 'Transfer' (refers to the leg not in contact with the ground) [6].

In this paper we considered Trotting configuration for further analysis where L1 and R2 form a pair of Support and L2 and R1 form a pair of Transfer while in motion. The 3D model of a quadruped robot is shown in Fig.2

Table.1.Phase relationship of locomotion patterns

Transitions	**L1** *Left fore leg*	**R1** *Right fore leg*	**R2** *Right hind leg*	**L2** *left hind leg*
Walk	0	π	$\frac{\pi}{2}$	$\frac{3\pi}{2}$
Trot	0	π	0	π
Bound	0	0	π	π
Gallop	0	$\frac{\pi}{2}$	π	$\frac{3\pi}{2}$

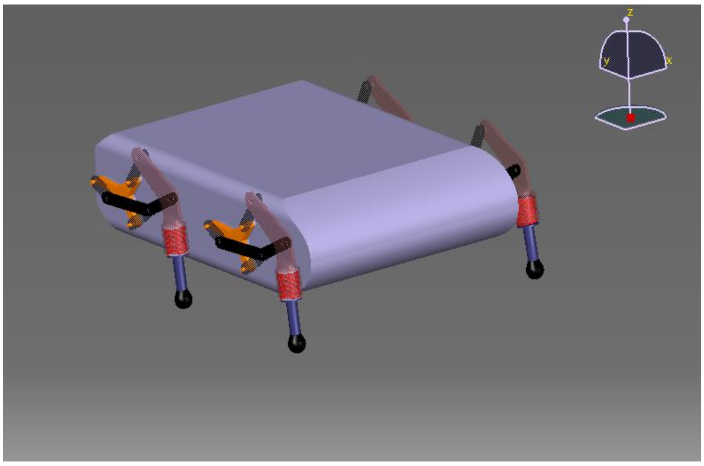


Fig.2. Modelling of the quadruped Robot

3. Selection of Link lengths

The generation of output trajectories of a mechanism can be visualized by the variation in link angles and link lengths. A small change in any of these parameters results in an entirely new trajectory. This leads to the implication of generating different motions. The variation in the combinations of the link lengths and the link angles α and β generates different trajectories. The line diagram of the Klann mechanism is shown in Fig.3.

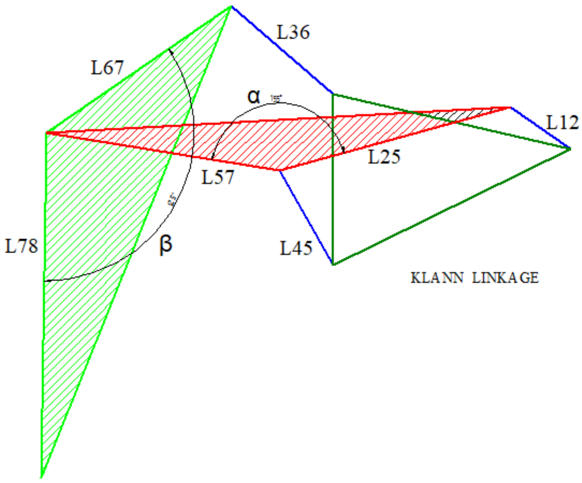


Fig.3. Line Diagram of Klann Mechanism

The general motion of any fixed gait pattern involves Standard Motion, Climbing Motion, Pecking Motion, Digging Motion and Jam avoidance Motion shown in Fig.4. The trajectories can be configured by changing the parameters. The Standard Motion Curve is the common walking motion encountered with the usage of Klann Mechanism as legs. This is mainly suitable for even terrains. When the terrain is steep, Climbing Motion Curve is implemented as the landing height of the leg as it strikes, is lower compared to the Standard Curve thus enabling a smooth climb. When there are uneven surfaces to explore, it is more suited to implement a Pecking Motion Curve due to the increased striking force of the leg. As the application concerns to digging the surface, the main focus is to pull back the remains as dug. This can be achieved with the implementation of a motion curve that is like to have a wide lower curve. Digging motion Curve hence is suitable for this purpose. As the obstacles that are likely to cause instability in legged robots increases, they have to be avoided. By the usage of Jam Avoidance Motion Curve, the robot will be capable of navigating with larger leaps.

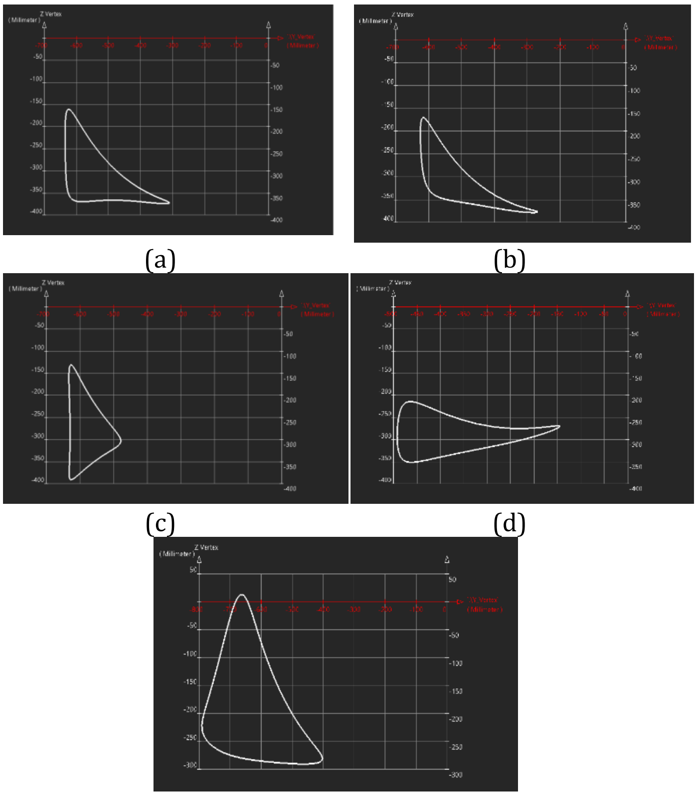
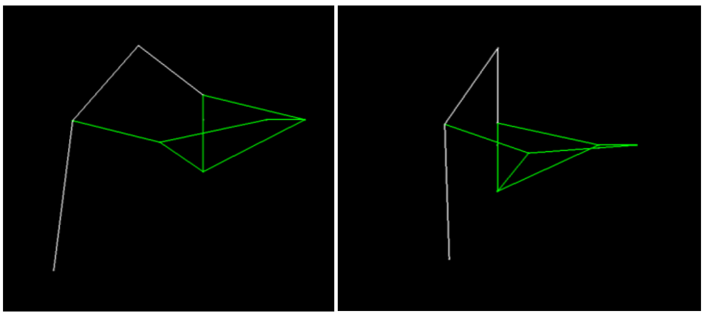


Fig4. Trajectories for different motion. (a) Standard Curve (b)Climbing Curve (c)Pecking curve (d)Digging Curve (e)Jam Avoidance Curve

In the present work, the link lengths of the Klann mechanism are suitably selected keeping the link angles constant. The trot pattern movement of the quadruped robot is analyzed for the variation of link lengths. The positions of the links for the crank angle at 0 rad and π rad is shown in Fig.5. The variation of link lengths are carried out by keeping the link angles constant(α =155°, β = 125°). The pattern of variation of end effector height and width are tabulated in the Table.2 and Table.3.



(a) (b)

Fig.5. Position of the crank (a) Crank at Zero rad (b) Crank at π *rad*

Table.2.Variation of end effector height

Lengths (mm)	Variation of end effector height					
	L12	L36	L45	L25	L57	L67
70	163.7	-	-	-	-	-
80	188.1	-	-	-	-	-
90	222.1	-	-	-	-	-
100	-	-	-	-	-	-
110	-	-	188.1	-	-	-
120	-	-	201.3	-	-	-
130	-	220.3	213.6	-	-	-
140	-	210.8	225.1	-	-	-
150	-	201.3	231.6	-	-	-
160	-	191.9	258.1	-	-	-
170	-	179.6	291.8	-	-	-
180	-	174.9	295.9	-	-	-
190	-	168.2	-	-	-	-
200	-	165.4	-	-	-	-
210	-	154.9	-	-	-	-
220	-	146.5	-	-	154.1	-
230	-	140.8	-	-	175.8	-
240	-	135.2	-	-	178.6	-
250	-	132.3	-	-	188.1	187.2
260	-	-	-	194.7	193.8	200.1
270	-	-	-	201.3	197.5	202.1
280	-	-	-	212.1	201.3	210
290	-	-	-	211.7	214.6	216
300	-	-	-	223.3	-	-
310	-	-	-	239.2	-	-

Table.3.Variation of end effector width

Lengths (mm)	Variation of end effector width					
	L12	L36	L45	L25	L57	L67
70	199.3	-	-	-	-	-
80	242.5	-	-	-	-	-
90	328.7	-	-	-	-	-
100	-	-	-	-	-	-
110	-	-	354.3	-	-	-
120	-	-	268.6	-	-	-
130	-	259.9	212.8	-	-	-
140	-	285.6	190.1	-	-	-
150	-	268.1	169.1	-	-	-
160	-	277.4	134.1	-	-	-
170	-	280.9	115.9	-	-	-
180	-	270.7	94.59	-	-	-
190	-	275.7	-	-	-	-
200	-	288.2	-	-	-	-
210	-	296.7	-	-	-	-
220	-	302.6	-	-	200	-
230	-	311.7	-	-	220.9	-
240	-	313.7	-	-	242.5	-
250	-	318.4	-	-	249.4	290.1
260	-	-	-	369.5	275.1	266.4
270	-	-	-	268.1	276.3	246.2
280	-	-	-	234.3	284.4	231.07
290	-	-	-	212.1	301.9	287.12
300	-	-	-	177.1	-	-
310	-	-	-	165.5	-	-

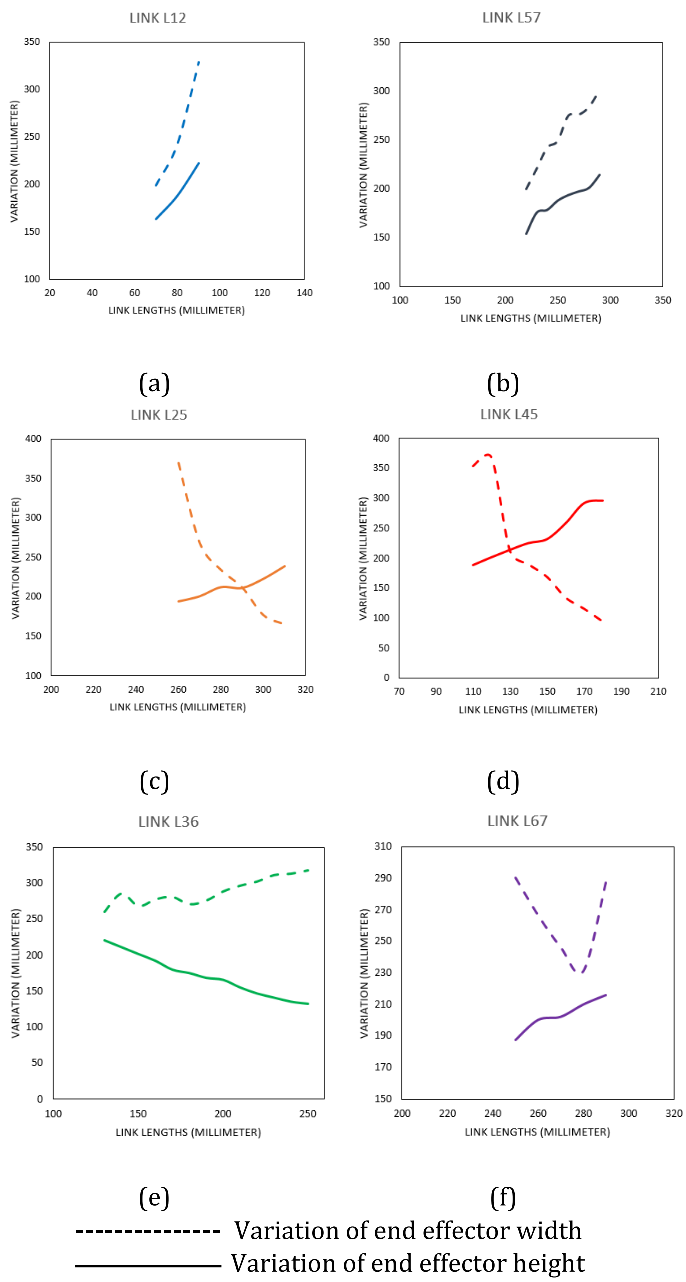


Fig.6.Representation of variation in link length of (a) End effector Height (b) End effector Width

The pictorial representation of the variation of end effector height and width is shown in Fig.6. It can be seen that every individual link has its own limitation to its maximum value as well as minimum value. In a fixed range of their lengths, the responses can be recorded. The links of the Klann mechanism can be grouped based on their response in the change of their lengths. With the increase in the link lengths of Links L12 and L57, both height and width can be seen increasing. Similarly in the case of Links L25 and L45, the width of the output trajectory decreases and the height increases with increase in the length. In Link L36, the height of the output curve decreases while the width increases. The ripples in the variation of the width are due to the increase in the curvature's tail height as seen in fig (4d). The trend in the width, changes from downhill to uphill in case of L67 with the increase in its length.

For the usage of Klann Mechanism for a "Trot" configuration, the above variations can be manipulated to generate a "Pecking Curve". Here, pecking curve is considered so as to match the speed of the quadruped robot with that of an average trotting speed which is nearly 3.6m/s [13]. From the above observation, the selection made is L12 = 90mm, L36 = 150mm, L45 = 145mm, L25 = 310mm, L57 = 232mm and L67 = 255mm. In this kind of motion, a significant amount of force is applied by the leg on to the ground. As a result, the leg experiences an equivalent amount of ground reaction force. A leg fitted with a spring mass damper system acts as an efficient medium for the utilization of this reaction force. Below shows a modelled individual leg of a quadruped with link lengths to the pecking motion configuration

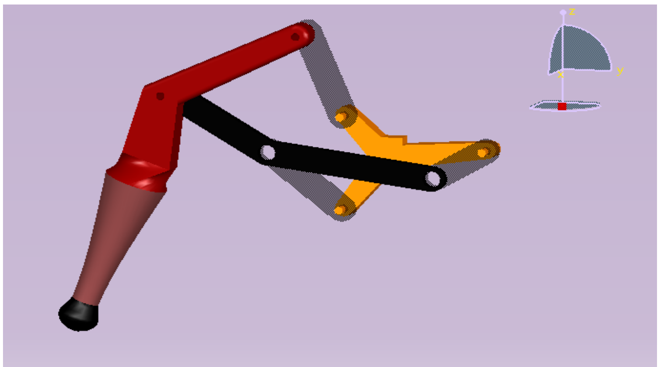


Fig.7: Individual leg of the quadruped robot with spring element

4. Dynamic Consideration

Movement in the quadruped will involve transfer of forces between the legs. When a leg applies force to the ground, an equal amount of reaction force is felt by the leg. In a pecking motion, the force with which the leg hits the ground is more compared to Standard Klann motion and other configurations. When this is considered, the leg experiences higher amount of force as a consequence of which the impact on the leg is more. This relates to the concept of impulse which is equal to the product of force and time for a particular interval of time. To decrease the amount of impact on the leg, it is necessary to increase the time interval for which the leg strikes the ground. By this, the impulse reduces. This can be achieved by the addition of an external spring component to the leg. Now, as the leg (L78) applies force to the ground, the spring mass damper system effectively absorbs the energy resulting in an increased impact duration. By modelling the leg and by studying the impact forces with and without the external spring element, the reduction in the reflex force can be studied.

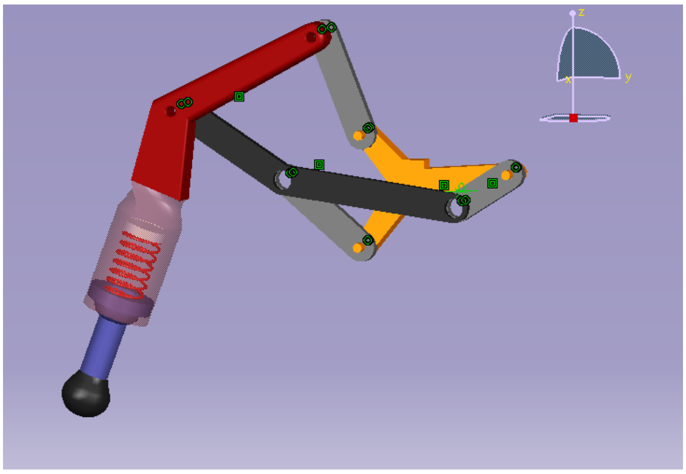


Fig.8: Individual leg of the quadruped without spring element

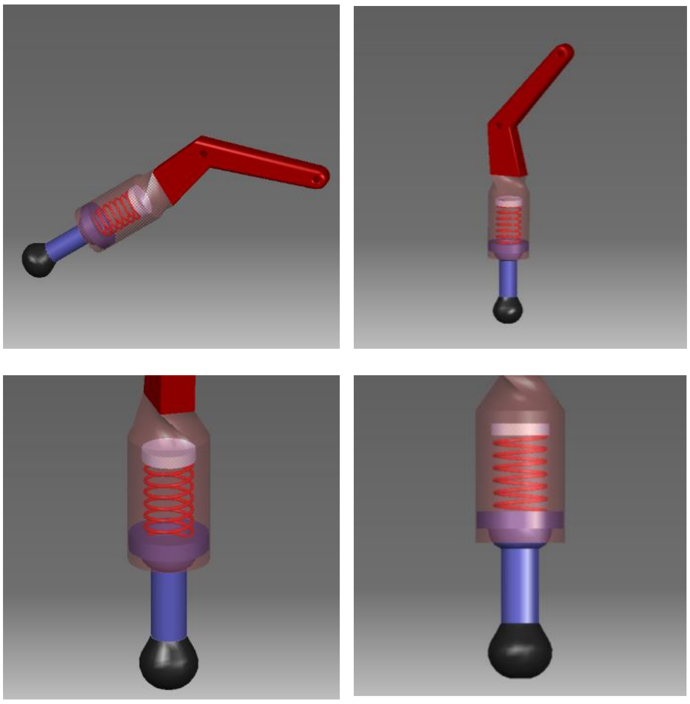


Fig.9: Views of individual leg with Spring element

This leg can be modeled and analysed as

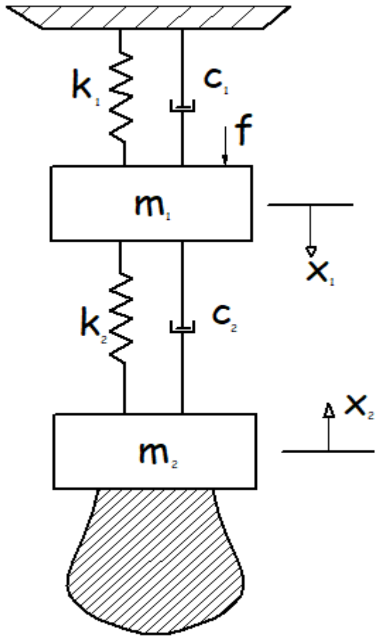


Fig.10. Spring Mass Damper system

Where,

m_1=Mass of the leg

k_1=Inherent spring stiffness of the material

c_1=Damping constant of the material

m_2=Mass of the external spring

k_2=Stiffness of external spring

c_2=Damping constant of external spring

f =Force acting on spring

x_1=Displacement of mass 1

x_2=Displacement of mass 2

$$m_1\ddot{x}_1 + c_2\dot{x}_2 + \dot{x}_1(c_1 + c_2) + k_2x_2 + x_1(k_1 + k_2) = f \quad (1)$$

$$m_2\ddot{x}_2 + c_2\dot{x}_2 + k_2x_2 + c_2\dot{x}_1 + k_2x_1 = 0 \quad (2)$$

Where $\dot{x}_1 = first\ derivative\ ;\ velocity$
$\ddot{x}_2 = second\ derivative\ ;\ accerleration.$

In the s-domian,

$$\left(m_1s^2 + (c_1 + c_2)s + (k_1 + k_2)\right)X_1(s)$$

$$+(k_2 + c_2s)X_2(s) = F(s)$$

$$(m_1s^2 + c's + k')X_1(s) + (k_2 + c_2s)X_2(s) = F(s) \quad (3)$$

$$(m_2s^2 + c_2s + k_2)X_2(s) + (k_2 + c_2s)X_1(s) = 0 \quad (4)$$

$$(m_1s^2 + c's + k')\left[\frac{m_2s^2 + c_2s + k_2}{k_2 + c_2s}\right](s)$$
$$+(k_2 + c_2s)X_2(s) = F(s)$$

$$X_2(s)\begin{pmatrix} (-m_1m_2)s^4 - (m_1c_2 + m_2c')s^3 \\ +(c_2{}^2 - m_1k_2 - c_2c' - m_2k')s^2 \\ +(2k_2c_2 - k_2c' - k'c_2)s + (k^2 - k'k_2) \end{pmatrix}$$
$$= F(s)[k_2 + c_2s]$$

As we are much concerned about the mass of the leg with respect to the displacement x_2, we get the transfer function as

$$\frac{X_2(s)}{F(s)} = \frac{k_2 + c_2s}{\begin{matrix}[(-m_1m_2)s^4 - (m_1c_2 + m_2c')s^3 \\ + (c_2{}^2 - m_1k_2 - c_2c' - m_2k')s^2 \\ + (2k_2c_2 - k_2c' - k'c_2)s + (k^2 - k'k_2)]\end{matrix}}$$

When a force f acts on the system, the the reaction force on the system is $m\ddot{x}$. As we are to study the force versus time response of the leg, the reaction to the applied force is $m_1\ddot{x}_2$. By multiplying s^2 to the above system response, we get the acceleration $\ddot{x}_2$. To this value, a scalar multiplication of the mass of the leg would result in the response of the reaction force on the leg for the applied force f.

$$\frac{[m_1s^2]X_2(s)}{F(s)} = \frac{[m_1s^2]k_2 + c_2s}{\begin{matrix}[(-m_1m_2)s^4 - (m_1c_2 + m_2c')s^3 \\ + (c_2{}^2 - m_1k_2 - c_2c' - m_2k')s^2 \\ + (2k_2c_2 - k_2c' - k'c_2)s + \\ (k^2 - k'k_2)]\end{matrix}}$$

$$\frac{X_2{}'(s)}{F(s)} = \frac{m_1k_2s^2 + m_1c_2s^3}{\begin{matrix}[(-m_1m_2)s^4 - (m_1c_2 + m_2c')s^3 \\ +(c_2{}^2 - m_1k_2 - c_2c' - m_2k')s^2 \\ + (2k_2c_2 - k_2c' - k'c_2)s \\ +(k^2 - k'k_2)\end{matrix}} \quad (5)$$

Without the addition of the external spring, the system can be modelled as,

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 = f$$

$$X_1(s)[m_1s^2 + c_1s + k_1] = F(s)$$

$$\frac{X_1(s)}{F(s)} = \frac{1}{m_1s^2 + c_1s + k_1}$$

$$\frac{X_1(s)}{F(s)} = \frac{1}{m_1s^2[1 + \frac{c_1}{m_1s} + \frac{k_1}{m_1s^2}]}$$

$$\frac{[m_1s^2]X_1(s)}{F(s)} = \frac{1}{[1 + \frac{c_1}{m_1s} + \frac{k_1}{m_1s^2}]}$$

$$\frac{X_1{}'(s)}{F(s)} = \frac{m_1s^2}{m_1s^2 + c_1s + k_1} \quad (6)$$

By considering the leg to be made of aluminium, an estimate can be obtained for the values of spring constant and damping coefficient. Assuming a damping factor of 0.55,

$m_1 = 3\ kg$	$m_2 = 0.01\ kg$
$k_1 = 11052631.58\ N/m$	$k_2 = 100\ N/m$
$c_1 = 6334\ Ns/m$	$c_2 = 2\ Ns/m$

For any system, the stability is determined by the pole-zero plot. The poles always exist in a conjugate pair. The system is said to be stable when the poles lie on the second and third quadrant. In this case, the curves in the time domain decrease exponentially with time. As a result, the system comes to its equilibrium state. When the poles lie on the first and fourth quadrant, the time domain curves increase exponentially with time signifying the exponential increase in the response of the system which is unstable.Since the poles here are on the second and third quadrants, the system is proving to be stable.

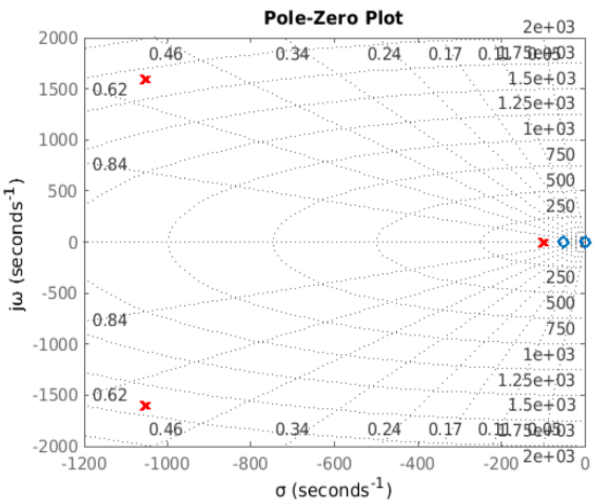


Fig.11.Pole-Zero plot for the system

Further, the response of the system can be analysed with the help of impulse plot. This plot indicates the response of the system for a very short interval of time as the force is applied.The response of the modeled system is shown in equation (5) and (6),

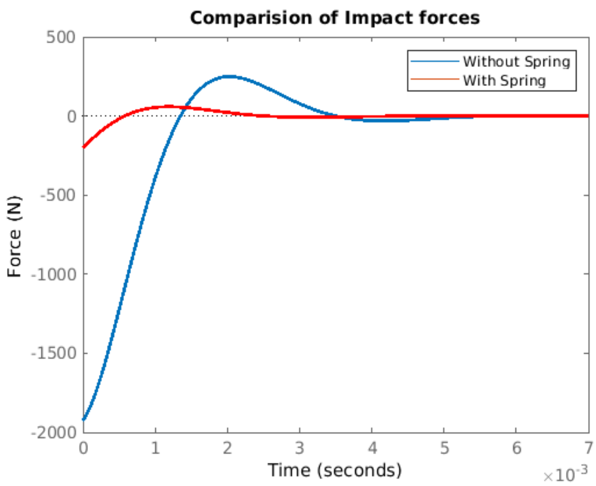


Fig.12. Comparison of impact forces with and without spring

The responses of the system with respect to time with and without spring is as shown in Fig.12. The result shows that by the inclusion of the spring element in the legs of the robot , the impact force is reduced by 89.41%pecent. A faster response can be achieved by radially increasing the position of the pole. This can be done by increasing the value of spring constant within the limit of response.
The equations for the above system are,

$$\begin{bmatrix}\dot{z}_1\\ \dot{z}_2\\ \dot{z}_3\\ \dot{z}_4\end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 1\\ -\frac{k_1+k_2}{m_1} & -\frac{c_1+c_2}{m_1} & -\frac{k_2}{m_1} & -\frac{c_2}{m_1}\\ 0 & 1 & 0 & 1\\ -\frac{k_2}{m_2} & -\frac{c_2}{m_2} & -\frac{k_2}{m_2} & -\frac{c_2}{m_2}\end{bmatrix}\begin{bmatrix}z_1\\ z_2\\ z_3\\ z_4\end{bmatrix} + \begin{bmatrix}0 & 0\\ \frac{1}{m_1} & 0\\ 0 & 0\\ 0 & 0\end{bmatrix}\begin{bmatrix}f\\ 0\end{bmatrix}$$

Where,

$$\begin{bmatrix}z_1\\ z_2\\ z_3\\ z_4\end{bmatrix} = \begin{bmatrix}x_1\\ \dot{x}_1\\ x_2\\ \dot{x}_2\end{bmatrix}$$

The output is expressed as,

$$x = CZ$$

$$[x\ ] = [C]\begin{bmatrix}z_1\\ z_2\\ z_3\\ z_4\end{bmatrix}$$

Where, in the need of displacement we have

$C = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}$ and in case of velocity we have

$C = \begin{bmatrix}0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$

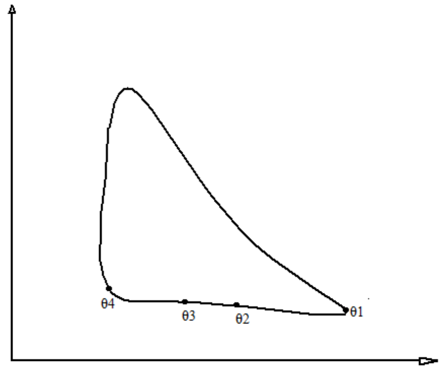


Fig.13. Representation of crank position in the standard Klann Curve

As we can see that the Standard Curve can be visualised as an interpolation of four distictinctive points i.e., the crank angles at different position. Here $\theta_1$represents the start of the curve where as $\theta_4$represents the ending of the curve. Similarly different motion curves have different location of these four points. Now, as there are four different points of interest, it is needed to use a third degree polynomial for the interpolation. We can write the cubic polynomial as a function of time t . This approach has already been successfully used in the community [11].

$$\theta(t) = a_0t^3 + a_1t^2 + a_2t + a_3 \quad (7)$$
$$\dot{\theta}(t) = 3a_0t^2 + 2a_1t + a_2$$
$$\ddot{\theta}(t) = 6a_0t + 2a_1$$

Consider, θ_i = initial crank angle and$\dot{\theta}_i$ and $\ddot{\theta}_i$ as the initial angular velocity and acceleration of the crank respectively. Similarly, by considering θ_f = final crank angle and $\dot{\theta}_f$and $\ddot{\theta}_f$ as the final angular velocity and acceleration of the crank respectively,

$$\theta_i(t) = a_0t_i^3 + a_1t_i^2 + a_2t_i + a_3$$
$$\dot{\theta}_i(t) = 3a_0t_i^2 + 2a_1t_i + a_2$$
$$\ddot{\theta}_i(t) = 6a_0t_i + 2a_1$$

Now, we get $X = TA$

$$A = T^{-1}X$$

$$\begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} t_i^3 & t_i^2 & t_i & 1 \\ 3t_i^2 & 2t_i & 1 & 0 \\ 6t_i & 2 & 0 & 0 \\ t_f^3 & t_f^2 & t_f & 1 \\ 3t_f^2 & 2t_f & 1 & 0 \\ 6t_f & 2 & 0 & 0 \end{bmatrix}^{-1} \begin{bmatrix} \theta_i \\ \dot{\theta}_i \\ \ddot{\theta}_i \\ \theta_f \\ \dot{\theta}_f \\ \ddot{\theta}_f \end{bmatrix}$$

From the above equation, we can compute the values of a_i $(i = 0, 1, 2, 3)$ which can be plugged in to the basic interpolation function as in equation (7) to obtain the trajectories.

5. CONCLUSIONS

The various kinds of gait transitions of the Klann Mechanism for different configurations were studied. It was observed that the output trajectories can be varied by varying the link lengths. The Klann mechanism was studied for minimum and maxiumum movements of the links and was observed that all the movements were distinct and precise. The trajectories of the mechanism gives a clear information about different standard motions suitable for different terrains. Further, mathematical modelling of the leg is carriedout to analyse the ground reaction force acting on the leg . An attempt was done to reduce the reaction force acting on the leg. By the response of the system, it was seen that, endorsing the leg of the quadruped robot with an external spring lead to the reduction in the impact force on the leg by 89.41% . By the result in the reduction of impact forces on the leg, implementation of Trotting pattern for the quadruped robot for rough terrains can be efficienctly achieved.

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