Just A Robot

Design of a versatile walking robot module

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1. Abstract

Our objective here is to create a mechanical type walking robot module, which can be fitted with parts of diverse functionalities. This module is designed specifically to be fitted with various components, depending on the respective needs of the customers and in addition, also for higher energy efficiency. In this project, we will elaborate on the details and dimensions of construction, advantages, kinematic analysis of the legs and bottom profile, and static analysis. This design was conceived after weighing the pros and cons of other alternatives and working on the best design to fit all consumer needs.

2. Introduction

Walking robots are of great value to researchers for their ability to move over rough or uneven surfaces with ease, compared to their counterpart, i.e. wheels. Their applications have been studied with utmost interest for their use in lunar surfaces, and in remote location surveillance. One walking mechanism that stands out is the **Jansen's Linkage** mechanism; an 8-bar linkage mechanism developed by kinetic sculptor named Theo Jansen, Jansen uses this mechanism in his 'Beach beasts' to generate a smooth walking motion in them. But later on, this linkage has been studied for real world applications apart from arts.

Legged robots have come to our attention due to their abilities to surmount or deal with complex obstacles, high levels of mobility (changing direction while moving), active suspension using force-controllable actuators in confronting irregular terrains, manoeuvrability and terrain adaptability. In this report, we've selected the walking mechanism due to the various advantages it has over wheels.

Biomimicry

It is a design thinking process that involves getting inspiration from the natural world. Biomimicry has been incorporated into the design of our modern world; from bullet trains to aeroplanes, in curing diseases and in deep learning. Jansen Linkage mechanism borrows its inspiration from the phenomenon of evolution for the synthesis of the linkage. The proposed leg design has now established its place among other leg systems of the nature.

Existing Technology

Presently, robot modules aren't mass produced anywhere, and are rarely available even as individual units. The market for such a product is wide open. Presently, it's quite difficult to test out the effectiveness of robot add-ons. Robots have only been used for large scale purposes like manufacturing and this product targets such left out niches.

Advantages of Jansen Linkage Mechanism

Jansen Linkage mechanism has all advantages of walking mechanisms over wheels. These include:

- Ability to move on different types of terrain such as snow, mountain, desert, etc.
- Better payload to weight ratio

- Maximum efficiency of moving
- Greater mobility and speeds
- Less environmental damage (both from paving and erosion)

Another advantage of walking mechanism over wheeled ones is their ability to overcome obstacles. Local maximas and minimas can be easily avoided by stepping over them. This results in lesser loss compared to wheeled mechanisms and helps in maintaining constant velocity through rough terrains

Compared to other walking mechanisms, Jansen Linkage mechanism is much smoother and can carry loads with relatively lower forces.

Selection (Pugh Matrix)

To ideally select a mechanism to rank it based on other existing technologies, we chose to compare the following:

Klann Mechanism: A walking mechanism. The gait of this particular leg system resembles that of a spider, with robots possessing typically eight legs.

Rocker-Bogey Mechanism: A wheeled mechanism involving a movable wheel link attached to a rigid frame of an angled link with a wheel at each end. This is primarily used by NASA in it's new rovers.

Theo Jansen Mechanism: A walking mechanism invented by Jansen, it was a mechanical and artistic breakthrough into a new area. The COM of each leg doesn't vary much conserving energy. The input is a crank and it has one DOF.

			Alternatives		
Criteria	Weightage	Baseline	Rocker- Bogey Mechanism	Klann Mechanism	Theo Jansen Mechanism
Maintenance	3	0	+	0	–
Usability in Terrains	5	0	0	+	+
Stability	5	0	+	–	0
Efficiency	5	0	0	0	+
No. of Actuators	4	0	0	+	+
Steering Capability	3	0	+	–	0
Weight	3	0	–	+	0
Cost	4	0	0	+	0
		Weighted Total	8	8	11
		Rank	2	2	1

Symbols	Relationship	Value
+	Better than baseline	1
0	About the same	0
–	Worse than baseline	-1

Guide:

1. Before you start, collect the two sets of data.
2. Insert the criteria on the left hand column.
3. Insert the alternatives on the top row.
5. Review the completed matrix to make the best decision

Note: You need only to fill the white, blue and yellow cells.

With this, we opted for the Jansen Mechanism.

3. Synthesis

This section will elaborate on how we arrived at our present design.

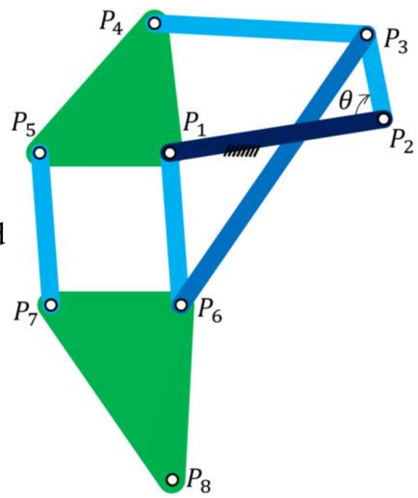
A. Initial Brainstorming

Our initial problem statement was to design a stair climbing wheelchair, which was low budget, stable and safe. A walking mechanism instead of wheeled climbing design was decided on, since wheeled climbing designs like the ones used by NASA were not stable, needed high graded, strong components and weren't cheap. Their advantage was the speed and that factor isn't needed in our desired wheelchairs. Jansens leg system was carefully designed by Jansen for many years, and researchers around the world had worked on different variations of his leg system.

B. Research

Market research around the world for stair-climbing wheelchairs revealed that high novelty mechanisms sold less. This trend was seen in all areas of the industry, with most people still preferring to go for designs which were perceived as 'basic, stable, non-gimmicky' instead of novelty products. Further research on the practical aspects of building a leg system to safely carry an human over sets of stairs showed that the number of leg systems for one wheelchair is more than 12, and each leg needed to be quite large. This made us rethink our problem statement.

C. New Problem Statement

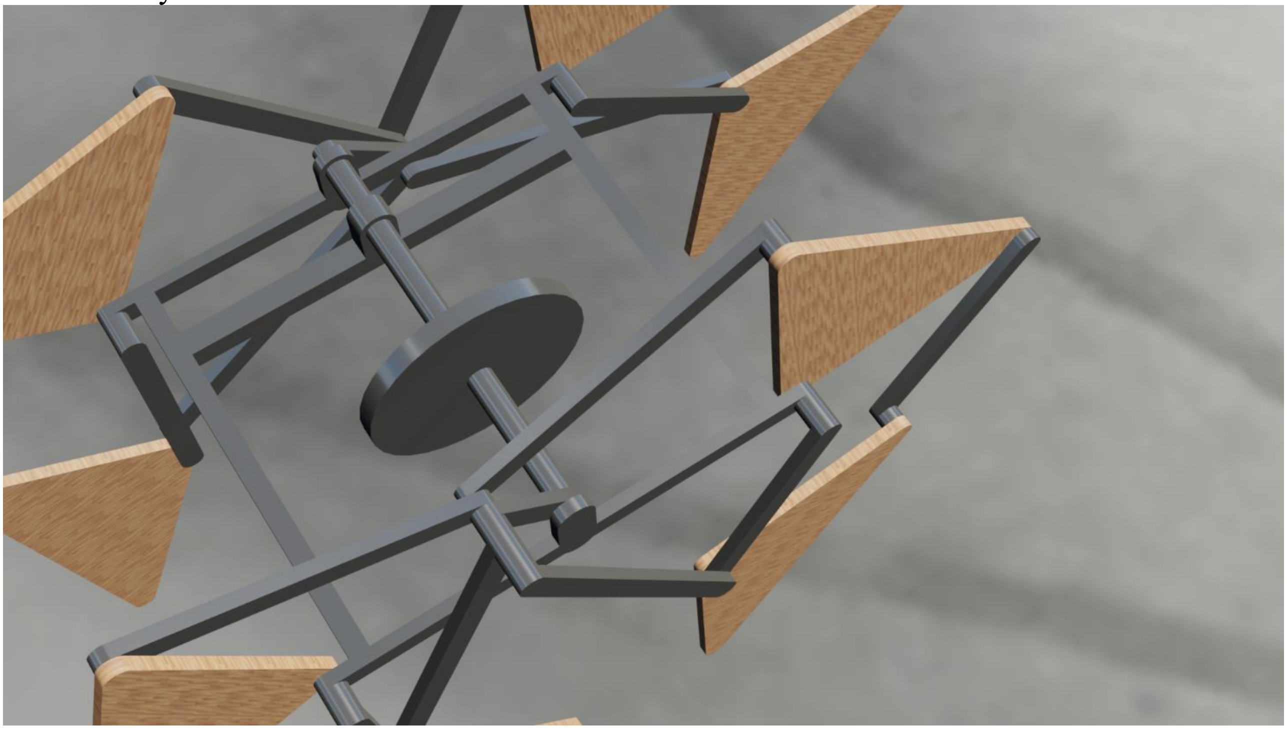


The new problem statement is 'to design a walking robot module which can be fitted with different parts of diverse functionalities' based on consumer needs. The ways a robot module can be used are limitless, ranging from the traditional needs for gait analysis and mobile robotic applications, to being used as a novelty product, to advanced robotic analysis and applications in harsh environments.

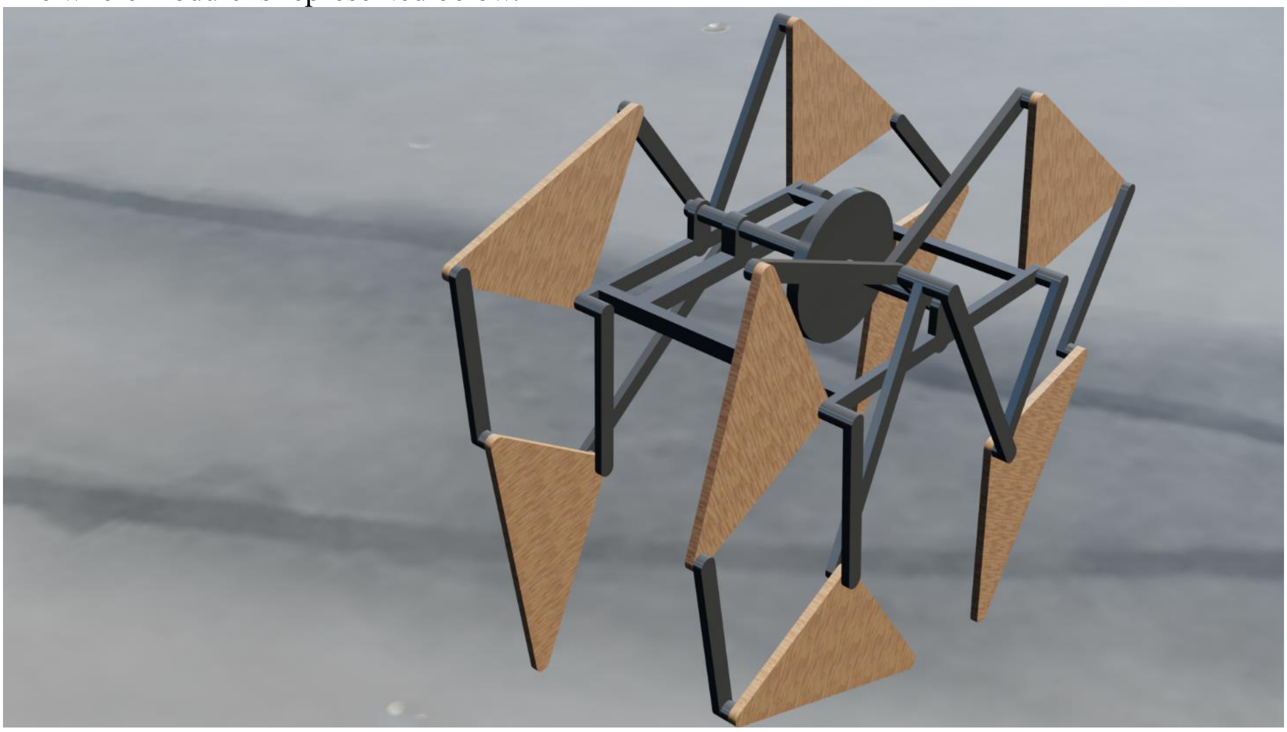
D. Proposed Design

The design consists of 4 leg systems, and the legs on the same side are paired to the same crank link, and out-of-phase to each other by a half rotation. This ensures stability of the system. The green areas are rigid in accordance with kinematic link laws.

The central frame is designed in a simple manner, connecting the 2 pairs of legs and adding a central rotary actuator to control the crank links on either side.



The whole module is represented below.



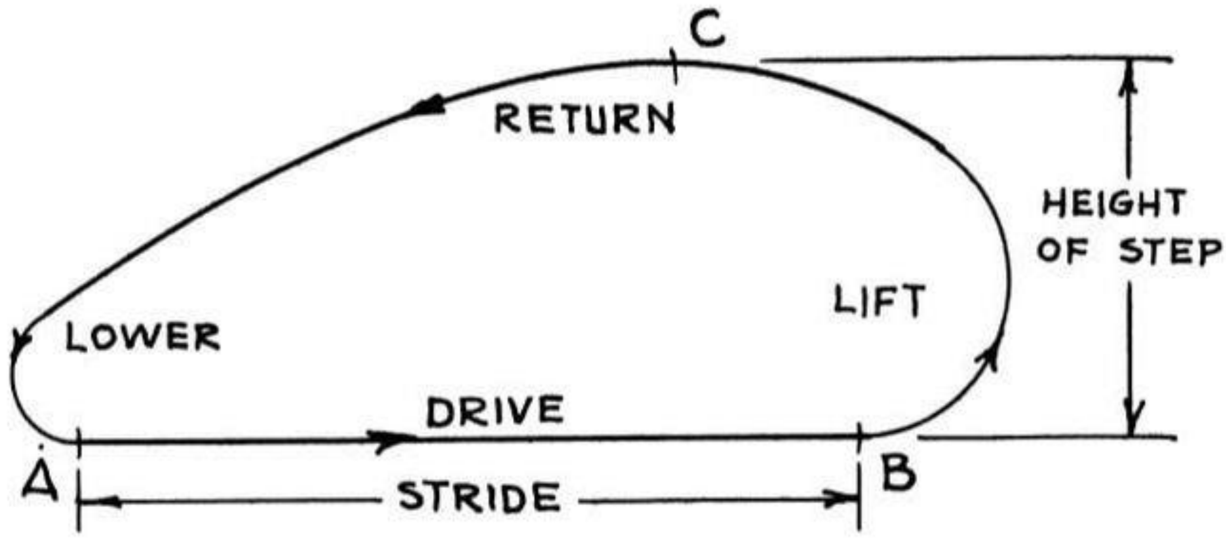
E. Locus

The curve generated by the leg through its motion i.e. the locus has 4 stages:

1. Stride – During this phase, the foot is in contact with the terrain.
2. Lift – In this phase, the leg is lifted to maximum height
3. Return – the leg moves in opposite direction w.r.t stride and is at maximum height

4. Lower stages – the leg is lowered from maximum height until it comes into contact with the terrain.

The curve, which is generated during the lifting and the lowering stage, holds the information on how the foot contacts the terrain.



Which is a desirable locus?

- Edgy locus results in more jerky motion of the leg.
- The locus should have minimum drag velocity (where drag velocity in this case, is defined as the maximum velocity difference between two points in stride phase). Having uniform velocity at all points of stride phase will ensure that the foot does not drag across the floor.
- The crank should be at uniform angular velocity. If it is not at uniform angular velocity, different feet will have different velocities at same locus locations.

With the above conditions in mind, a set of dimensions and parameters were arrived at which satisfy our requirements.

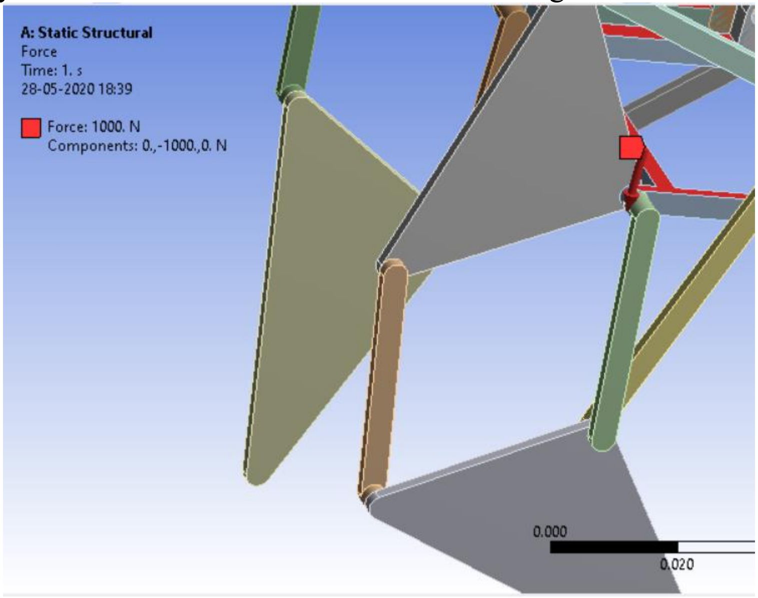
The parameters of Jansen Linkage are the length of its rods. The rod lengths decide the locus.

With the aid of kinematic Equations, the orbit of a TJL can be determined provided that the six parameters, i.e., a, b, c, d, Sx, Sy, are given. This is so called the forward problem. However, designing a TJL to generate a given orbit is an inverse problem, i.e., given the specification of an orbit to determine six rod lengths. It is hopeless to derive any analytical function to deal with this inverse problem.

Desirable orbits can be obtained by finding out appropriate rod lengths. Further calculations are discussed in the kinematic analysis of a leg system.

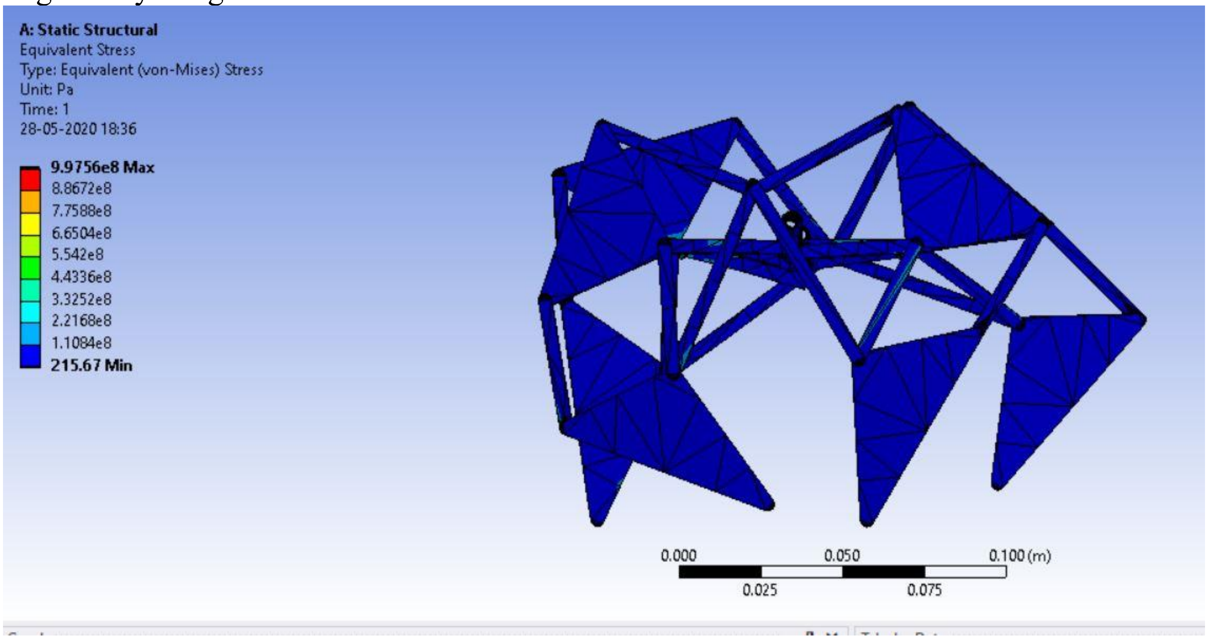
4. Static Analysis

Finite element analysis for the robot has been taken. The linkages are made from steel, and the load applied is 1000 N.

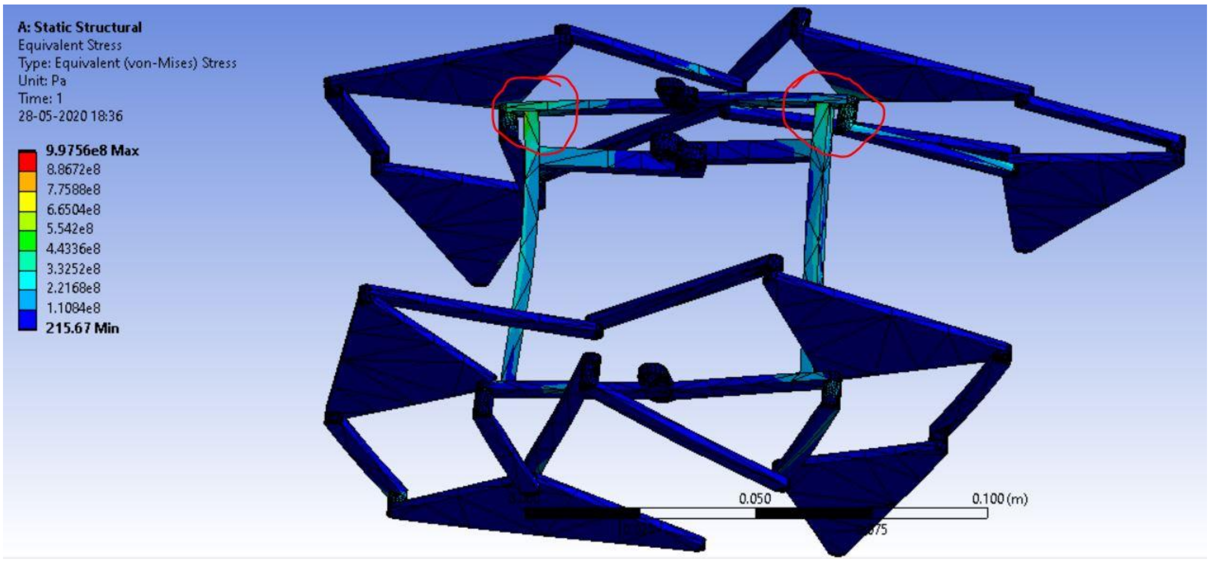


The force has been applied on the main frame of the robot, which connects the 4 legs. The bottom part of each leg has been taken as fixed support, since under static conditions those are the areas which will be static.

The maximum stresses develop at the joints connecting the frame and the legs which are at the middle, as expected. The average stress is within the material range to avoid failure with a very large safety margin.



With the inclusion of the rod which connects the 2 pairs of legs, the stresses at the joints are taken care of.



The highlighted regions bear the brunt of the load without a connecting rod and wheel, but with its inclusion the load gets distributed throughout the whole frame much more uniformly.

The results from the static analysis have proven that the robot will have no problem in carrying out any of its expected tasks. Also, it'll be able to equip any required sensors without any problems.

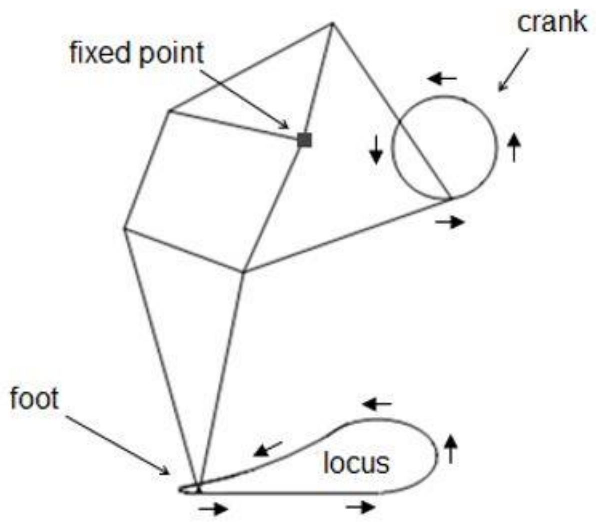
5. Kinematic Analysis

In this section, the dynamic analysis of a single leg system will be discussed, along with the loci of important points and nodes of the leg and the ideal dimensions. The leg has one DOF and it moves in the same path, provided none of the link lengths and initial angles change.

Overview

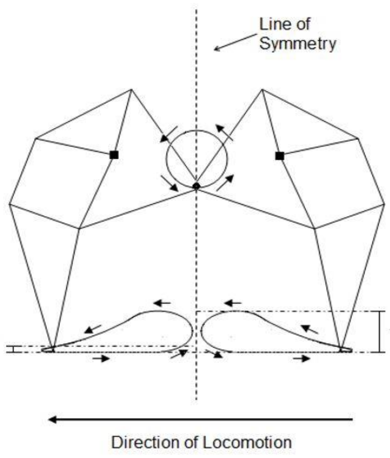
The leg consists of :

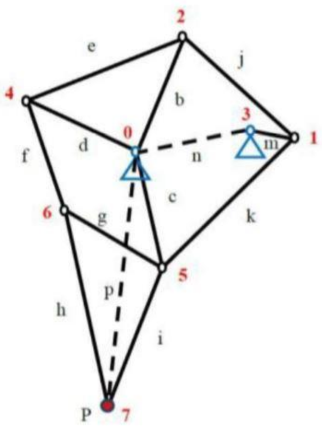
- A crank at uniform angular velocity. This is the driving force for the leg. The velocity of output locus is directly proportional to crank velocity.
- A fixed point. This is stationary in chassis frame of reference.
- Foot locus is the output point. This locus determines the motion of the whole robot, how big an obstacle it can overcome, how fast the frame moves and the energy efficiency of the process.



2 legs are coupled out of phase so that the whole system remains stable, such that when one leg is in contact with the ground, the other is stepping and vice versa.

This also greatly simplifies the control systems of the robot, since only one crank link has to be controlled and since that is at uniform angular velocity, the controls are basic at best for the module.



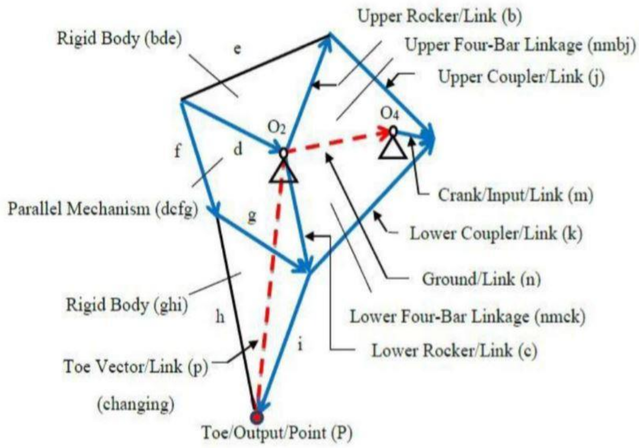


Numbering points for kinematic analysis

This figure denotes the numbering points, to be referred to for analysis. Each point is a node, and the analysis of nodes excluding the output node is also important for heavy duty applications and to further refine energy efficiency.
For more efficiency, the COM of the whole leg must remain at a constant height so that energy is conserved by not expending on potential energy. For this, analysis of all nodes is important too, but this analysis is too complicated for the present report.

The leg mechanism has a crank (m), two oscillating rockers (b,c), and two couplers (j,k), all connected by pivot joints. Each leg consists of six parts:

1) two three-bar linkages (triangles) bde and ghi, which are rigid bodies while the crank rotates
2) an upper and lower four-bar linkages (crank-rocker) nm-bj and nm-ck, respectively, whose governing equations of motion are similar to any other crank-rocker mechanisms
3) an open four-bar linkage dc-fg called parallel-like linkage because of its figurative resemblance to parallelogram
4) a rigid three-bar linkage ghi called foot
5) a ground, which is the link between the two pivoted fixed points (O_2O_4), represented by the dashed vector n
6) the interconnection points of links h and i, which is called the toe.



Calculations

The analysis of the leg will be done by taking the below mentioned initial dimensions from Jansen.

Table 3
Initial conditions for dynamic model of Jansen leg mechanism.

Variable	Initial value (°)
ϕ_0	0
ϕ_1	37
ϕ_3	122.49
ϕ_4	16.39
ϕ_6	144.37
ϕ_8	134.03
ϕ_9	65.92

Link lengths in Jansen leg mechanism in proportion to crank length.

Link	Length
Link-0 (crank)	$l_0 = 1.00$
Link-1	$l_1 = 3.33$
Link-2	$l_2 = 3.72$
Link-3	$l_3 = 2.63$
Link-4	$l_4 = 4.38$
Link-5	$l_5 = 3.27$
Link-6	$l_6 = 4.13$
Link-7	$l_7 = 2.45$
Link-8	$l_8 = 2.62$
Link-9	$l_9 = 2.77$
Link-10	$l_{10} = 2.67$
Link-11 (stationary)	$l_{11} = 2.59$

Put the origin of the general coordinate system at point O_2. The vector loop equation for a general 4-bar linkage "dc-ab" will be:

$$\vec{d} + \vec{c} - \vec{a} - \vec{b} = 0 \qquad (1)$$

using complex numbers Eq. 1 can be rewritten as:

$$de^{j\theta d} + ce^{j\theta c} - ae^{j\theta a} - be^{j\theta b} = 0 \qquad (2)$$

where {a,b,c,d} present the link lengths. Equation 2 can be solved for two unknown parameters, the angular positions of the rocker θ_b and coupler θ_a . These unknowns are functions of the links length {a,b,c,d} and the angle of the crank θ_c :

$$\theta_{\{a,b\}} = u_{\{a,b\}}(a, b, c, d, \theta_c) \qquad (3)$$

where $\theta_{\{a,b\}}$ means either θ_a or θ_b.

Since these are general parameters, they can be replaced by the parameters of different corresponding linkages under study.

$$Upper: \{a, b, c, d\} \triangleq \{b, j, m, n\} \qquad (4)$$

$$\{\theta_a, \theta_b, \theta_c, \theta_d\} \triangleq \{\theta_b, \theta_j, \theta_m, \theta_n\} \qquad (5)$$

$$Lower: \{a, b, c, d\} \triangleq \{c, k, m, n\} \qquad (6)$$

$$\{\theta_a, \theta_b, \theta_c, \theta_d\} \triangleq \{\theta_c, \theta_k, \theta_m, \theta_n\} \qquad (7)$$

$$PARL: \{a, b, c, d\} \triangleq \{f, g, c, d\} \qquad (8)$$

$$\{\theta_a, \theta_b, \theta_c, \theta_d\} \triangleq \{\theta_f, \theta_g, \theta_c, \theta_d\} \qquad (9)$$

For example, Eq. 2 can be written in terms of real and imaginary parts for the upper linkage:

$$n \cos \theta_n + m \cos \theta_m - b \cos \theta_b - j \cos \theta_j = 0 \qquad (10)$$

$$n \sin \theta_n + m \sin \theta_m - b \sin \theta_b - j \sin \theta_j = 0 \qquad (11)$$

For Eq. 10 and Eq. 11, the unknows $\{\theta_j, \theta_b\}$ are . From (10) and (11) we can find:

$$x\cos\,\theta_{\{j,b\}} + y\sin\,\theta_{\{j,b\}} \triangleq R\cos(\theta_{\{j,b\}} - \alpha) = A \quad (12)$$

where the constants "x", "y", "R", "α" and "A" are:

$$x = n\cos\theta_n + m\cos\theta_m, \qquad y = n\sin\theta_n + m\sin\theta_m \quad (13)$$

$$R = \sqrt{x^2 + y^2}, \quad \alpha = \tan^{-1}\left(\frac{y}{x}\right) \quad (14)$$

$$A_{\{j,b\}} = \frac{\{j,b\}^2 - \{b,j\}^2 + x^2 + y^2}{2\{j,b\}} \quad (15)$$

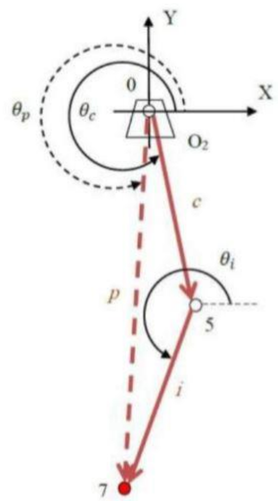
In (12) and (15), only one subscript inside the brackets will be considered at a time. Solving (12) will get us the angular position of the coupler and the rocker of the upper linkage. Similarly, $\{\Theta_k, \Theta_c\}$ the unknown parameters for the lower linkage can be found. Since triangle 'bde' has rigid body behaviour, the angle of Θ_d can be obtained using the Law of Cosines where Θ_e is known and Θ_b has been obtained from solving (12):

$$\theta_d = \theta_e + \theta_b = \cos^{-1}\left(\frac{b^2 + d^2 - e^2}{2bd}\right) + \theta_b \quad (16)$$

The outputs of the kinematic analysis of the upper and lower linkages $\{\Theta_c, \Theta_d\}$ are used as the inputs of the parallel-like linkage.

In the parallel-like linkage dc-fg, link d is presumed to play the same role as link n does in the analysis of the upper and lower linkages. However, its angle is not constant as the crank rotates. Similarly, applying the same method to the parallel-like linkage; separating equations into real and imaginary parts will give unknown parameters of this linkage which are $\{\Theta_f, \Theta_g\}$. The angular position Θ_g is the foot input.

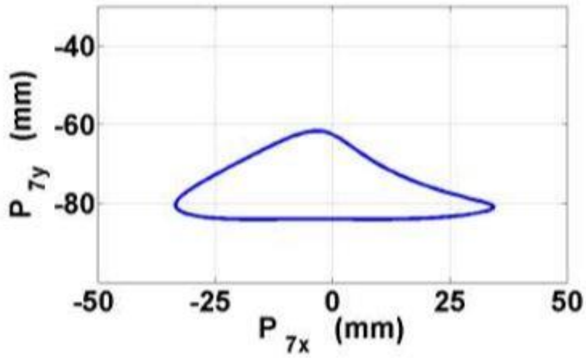
To plot the trace path of the foot, angular position of the variable dashed vector 'p' for each increment of crank rotation is to be found. This vector along with vectors 'c' and 'I' creates the triangle 'cip' in which the toe is located. The figure to the right represents the cip triangle.



The angle Θ_i can be found similarly to Θ_d. The vector loop equation for this triangle gives the angular position of the toe as:

$$\theta_p = \ln\left(\frac{ce^{j\theta c} + ie^{j\theta i}}{p}\right) \quad (17)$$

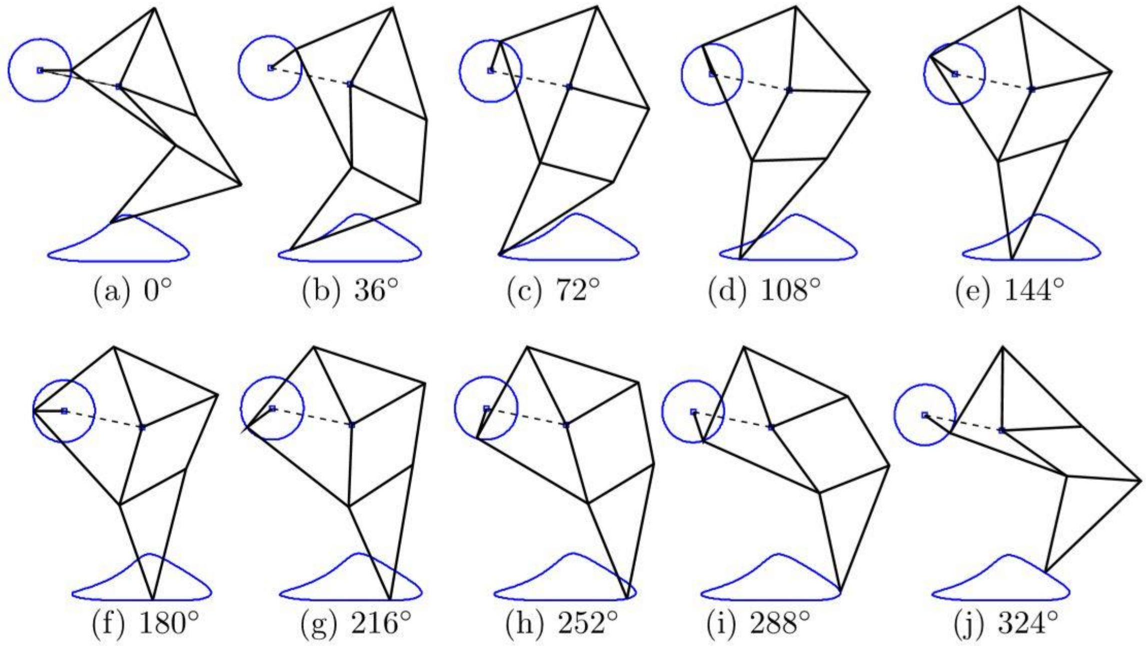
Hence, we get the locus of toe as:



The calculated step length proportional to crank radius 1 turns to be 4.5. And step height is approx.. 1.5. Hence, with by varying the crank radius:

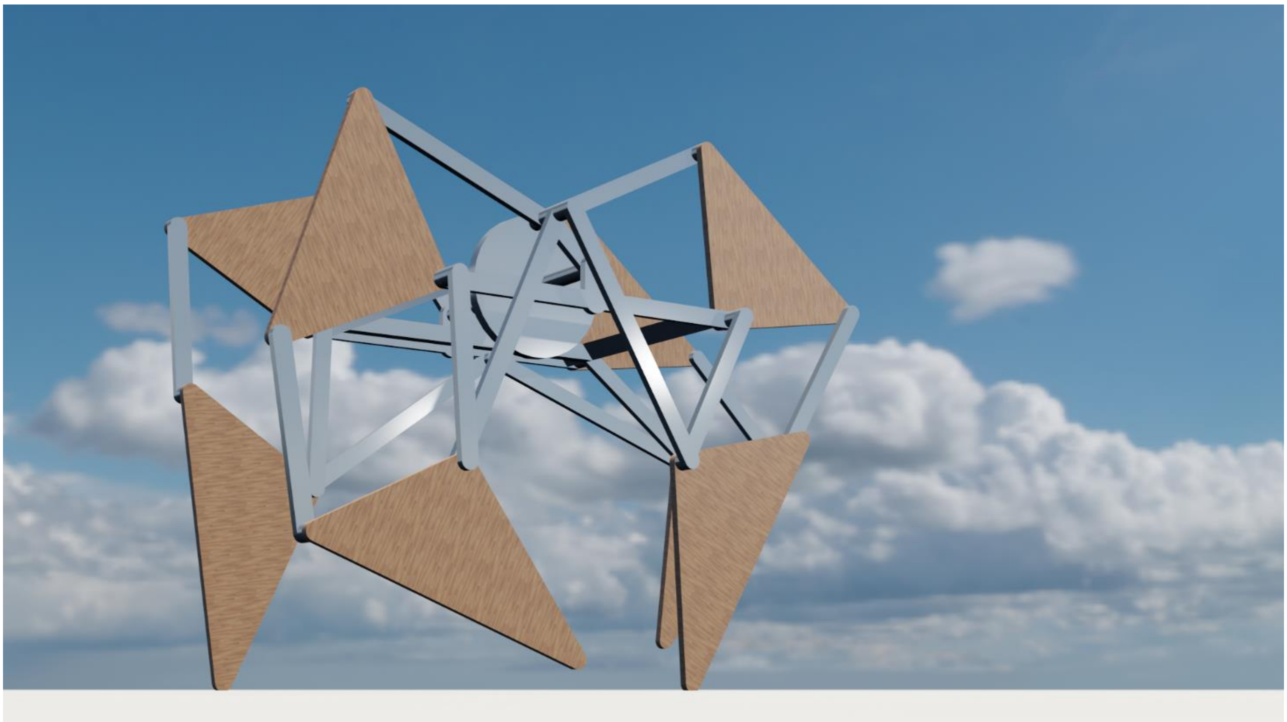
1) the speed of the mechanism propagation is varied (depends on the step length)
2) a terrain with max obstacle size (depends on how much the step height is)

A full rotation of the crank is demonstrated below.



6. Conclusion

This report presents the start to end process of the design and analysis of a walking robot module based on the Jansen leg mechanism. The module has various applications and the basic leg itself can be changed with linear actuators (for ex, to change crank radius for varying step length and height). A CAD model is shown below, demonstrating the novelty and simplicity of such a product design. With intermediate level market research ,we decided upon this model. Static analysis has further shown that this design has high load carrying capabilities, which is complimented by having this design as a robot module (instead of a wheelchair, hence miniaturizing).



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