Design, Simulation and Optimization of 4-Bar Linkage Walking Mechanism with Partial-Rolling Steps

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1. INTRODUCTION

Background

Robots are used in various fields such as demining robots in the military, mountain exploration robots, lawn mower robots, and vacuum cleaner robots. Among the types of robots that can move, the most frequently used are wheeled and legged robots.

Problem Statement

In designing a legged robot, it is necessary to find the optimal shape of the leg. There are two approaches, namely direct foot position control with software or fixed foot movement based on geometric construction.

In legged robots, the toe is usually modeled as a point with a small contact surface or foot, making it difficult to use on soft or uneven terrain. For difficult terrain, tank chains and large wheels are still the main choice. Meanwhile, the advantage of the foot is its ability to pass obstacles.

Goal

This research aims to find the optimal geometric shape in a walking robot mechanism design using legs that are made to resemble the rolling motion of a wheel in part of its steps to obtain the best constant speed and stepping pattern.

2. STUDY OF LITERATURE

Legged robots have various numbers of legs, commonly 2, 4, and 6 legs while 1 legged robot and robots with more than 8 legs are also found. A well known example is Theo Jansen's Strandbeest, utilizing what is later known as the Jansen's linkage. The Strandbeest is a mechanism using wind energy to drive the linkage. There are many researches to find the characteristics of the Jansen linkage [1]. Another example is BigDog, a four-legged robot which can traverse terrain impassable by wheeled robots, and its successors [2].

With more legs, the number of required motors are also increased, and subsequently the degree of freedom also increases, which means the movement is more flexible. However, additional motors also increase complexity and difficulty to control the robot. One approach to get smoother controlling is by fuzzy logic [3]. Usually, leg mechanisms have small pointed feet or small pads. To control the pads, further additional mechanisms are needed such as springs or two linkages connected together with parallelogram linkage proposed by Shigley [4].

Combining a simple linkage with a leg that has a large ground contact area can be a solution in robot design. Currently, there is no simple linkage application with broad legs that can be compared with wheels of off-road vehicles. This research seeks to produce a design that can combine simple linkage with the ability to walk on rough terrain using a leg shape that resembles a rolling motion. In the design, it is necessary to look for the best parameters, which will be sought with Particle Swarm Optimization (PSO). This method has been used in several robot geometry designs [5].

This research focuses on a linkage mechanism driven by a single motor. This mechanism has one degree of freedom, which means it can only go forward and backwards. There are several common designs with this type of linkage, which are as follows:

1. Klann Linkage

This linkage consists of five bars. One is the driving crank, two rockers which ends are connected to the body, and two connecting bars. The foot tip of the Klann linkage moves in a pattern shown in Fig. 1. This tip touches the ground for approximately half cycle. The Klann linkage is already used in several simple robot designs [6,7].

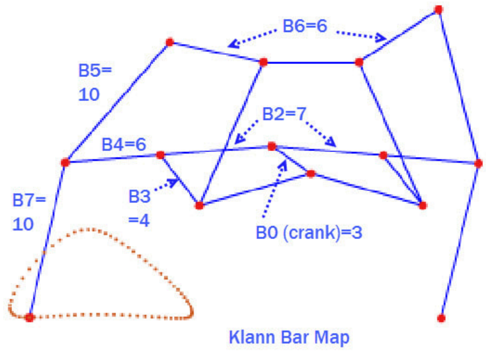


Figure 1: Klann linkage.

2. Jansen's linkage [8]

This linkage consists of 13 bars and 6 joints. This design is popular and already implemented in various robots, from toys to walking chairs. The overall shape resembles the gait of a natural walking animal. The design of Jansen's linkage is shown in Fig. 2.

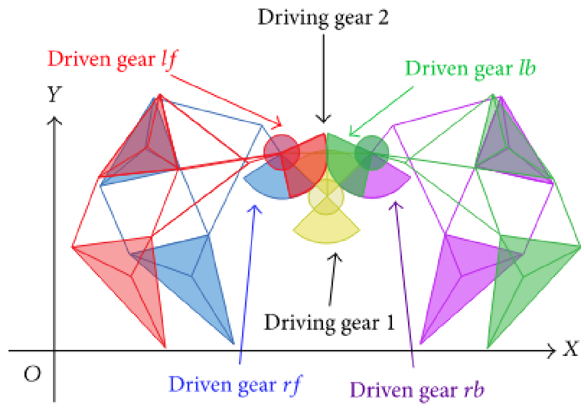


Figure 2: Jansen's linkage

3. Ghassaei linkage [9]

This design produces symmetrical stepping movement, but perhaps the complexity makes it rarely used in robotics. The design of Ghassaei linkage is shown in Fig. 3.

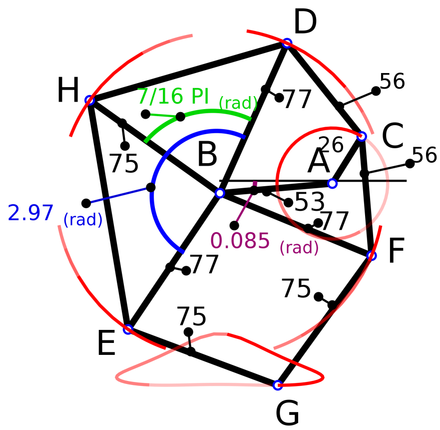


Figure 3: Ghassaei linkage.

4. Chebyshev lambda linkage [10, 11]

This linkage produces a smooth and flat walking movement, but the movement is produced above the mechanism. An effective implementation of this linkage is yet to be found. The design of Chebyshev linkage is shown in Fig. 4.

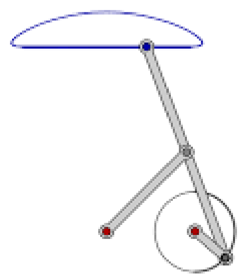


Figure 4: Chebyshev linkage

5. Strider linkage [12]

This linkage consists of 10 bars, namely 1 crank, 3 rockers, and 6 connectors. There is currently a limited implementation of this linkage, which is only made with LEGO. The foot movement of the Strider linkage is shown in Fig. 5. The designer of the Strider linkage already considered adding “toes” to the foot tip which is shown to improve the walking smoothness.

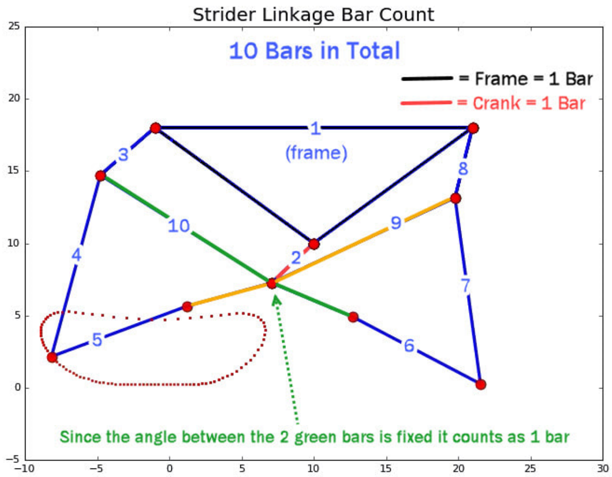


Figure 5: Strider linkage

3. METHODOLOGY

The majority of legged robots have practically one point as the foot tip. Other robots have foot pads to increase ground contact area, decreasing pressure and enabling it to walk on soft ground.

To improve the ability of a robot to traverse uneven or soft terrain, this research will study the usage of carefully shaped feet so that the stepping movement is like a rolling wheel. The concept is named “Rolling Step Linkage” in this paper.

Rolling Step Linkage Structure

In this research, a simple 4 bar linkage is chosen which can generate stepping-like movement, shown in Fig. 6. In this design, point 3 is the driving axis and bar 3-4 is the crank rotating with a constant rate. Point 1 is connected to the chassis, bar 1-2 is a rocker, and bar 2-4 is a connecting rod with the foot fixed to it. The optimization parameters are shown in Table 1.

Variable	Description	Minimum value	Maximum value
L12	Length of bar 1-2	10	100
L24	Length of bar 2-4	10	100
G	Ground height	20	100

	from point 3		
X1	X-coordinate of point 1	-40	40
Y1	Y-coordinate of point 1	-100	-10

Table 1: Optimization Parameters

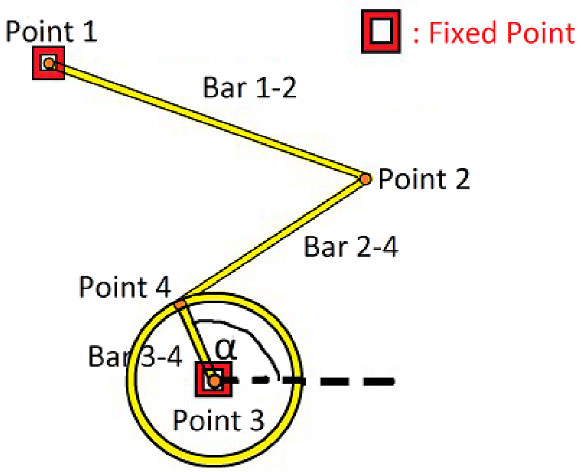


Figure 6: Four-bar linkage used in this research.

To construct the Rolling Step structure, first the coordinate of point 1, length of bars 1-2 (L12) and 2-4 (L24) are set. Point 3 is the coordinate origin. Point 4 location is calculated by rotating bar 3-4 for α radian with point 3 as pivot. Then, point 2 is determined by drawing a circle from center point 1 with radius L12, and another circle from center point 4 with radius L24. One of the intersection points of the circles is point 2.

Foot Curve Construction

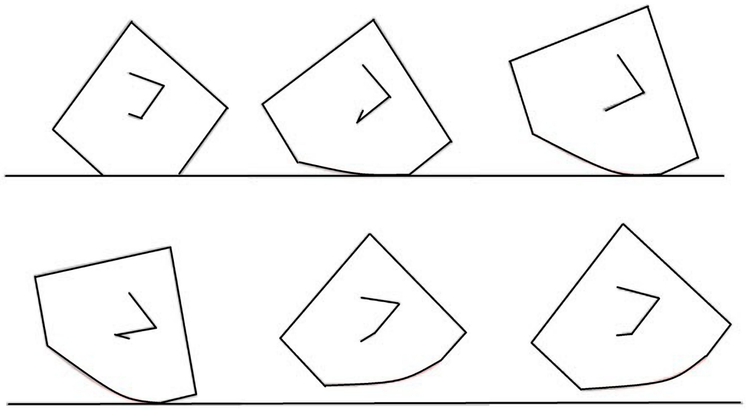


Figure 7: Steps of constructing the foot curve.

A rigid shape is attached to and moving with bar 2-4, as shown in Fig. 7. Initially 4 points represent the foot shape, named the polygon, with at least 1 point underground. Then, the polygon will move along with bar 2-4. For each time step, all points of the polygon are checked. If there are any points underground, the polygon is cut in a straight line according to the ground line. This process is repeated until the crank makes one full rotation and the polygon will take shape of the required foot shape for walking smoothly.

Ground contact phase

After the foot is shaped, bar 3-4 is rotated for another cycle. For all α steps, all points are checked whether there are any points touching the ground, by finding points that have the same y-coordinate as the ground. The portion of a cycle where the foot is in contact with ground is then calculated.

Walking Speed

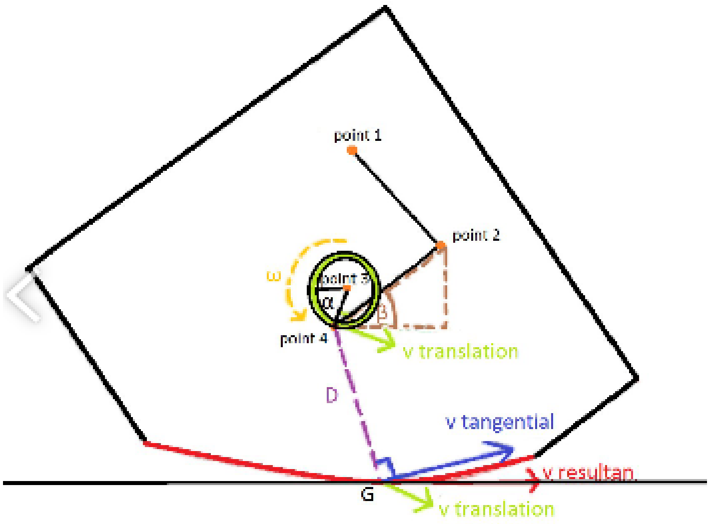


Figure 8: Kinematics diagram of the Rolling Step linkage.

To obtain the walking speed, the linkage is run and the instantaneous velocity of the ground contact point is calculated. The instantaneous velocity is calculated by:

$$v = v_{x\ tangential} + v_{x\ translation}$$

Translational velocity of point 4 is calculated from Δα (differential of α) and R (length of bar 3-4).

$$v_{translation} = \Delta\alpha \cdot R$$

Since only horizontal component of the velocity is needed, we get:

$$v_{x\ translation} = v_{translation} \cdot \sin\alpha$$

Tangential velocity is calculated from Δt (change in time), coordinates of point G (ground contact point), D (distance from point 4 to G), β (angle of bar 2-4 from horizontal), and Δβ (differential of β).

D is found using Pythagoras' formula:

$$D = \sqrt{\left(Y_4 - Y_G\right)^2 + \left(X_4 - X_G\right)^2}$$

$$\beta = \tan^{-1}\left(\frac{Y_2 - Y_4}{X_2 - X_4}\right)$$

$$\Delta\beta = \beta_{i+1} - \beta_i$$

To calculate horizontal component of tangential velocity, because the angle which line D makes with horizontal is the same as the angle between ground line and tangential velocity, the following equation is formed:

$$v_{tangential} = \Delta\beta \cdot D$$

$$v_{x\,tangential} = v_{tangential} \cdot \frac{Y_4 - Y_G}{D}$$

Distance travelled in 1 cycle

The distance travelled in one step is calculated by integrating the instantaneous velocity of the ground contact point. To avoid the optimization program maximizing this distance by enlarging the foot without limit, this distance is divided by the linkage's total height, which is the highest y-coordinate of the linkage calculated from the ground.

Velocity standard deviation

Standard deviation of speed will increase proportionally with the average speed of the linkage, so the algorithm will create shape with low velocity, to minimize the standard deviation. To overcome this, the standard deviation is divided by the average velocity so that the sdx value is not affected by the average velocity.

Step height

To calculate the step height, for every α the closest distance of the foot to the ground is searched. The maximum value of that distance is then taken as step height.

Linkage Height

A tall linkage increases the step distance, but it also increases the material needed to make the linkage. Therefore, the score is divided by the linkage height to prevent the algorithm from making a tall linkage.

Lowest position of point 2

In initial tries, it is observed that sometimes point 2 moves underground. It is later considered that a joint moving near the ground is not desirable. Therefore, the closest distance of point 2 to ground is included in the scoring system.

Overall scoring system

Every scoring component is given individual weights, then is combined by calculating the product. Weight of every component is the power of the component concerned. Components that want to be minimized are the denominator of the score, by assigning negative weights. Components that want to be maximized are assigned with positive weight. Important component so that it is assigned with large weight is the phase angle that hits the ground. Formulation of score is as follows:

$$Score = \prod_i s_i^{w_i}$$

With the component values of s_i are described in Table 2.

Table 2: Scoring components for optimization.

Component (i)	Description	Weight (w_i)
1	Distance travelled in one step	2
2	Ground contact phase	5
3	Step height	1
4	Overall height	-2
5	Velocity standard deviation	-3
6	Lowest position of point 2	0.5
7	Distance between point 1 and 4	0.5

8	Angular acceleration of bar 24	0.8

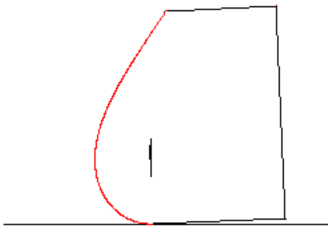
Particle Swarm Optimization [13]

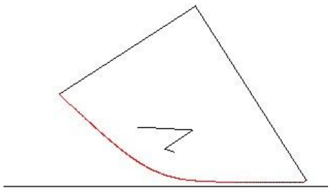
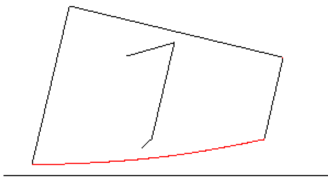
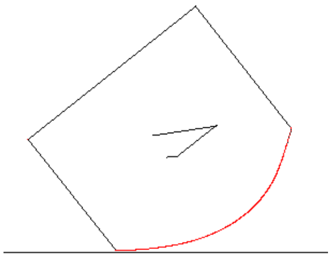
Particle swarm optimization is a method to get the highest score with particles. Particles resemble a linkage shape that is represented with 5 variables. Firstly, N particles are made in random positions then every particles' score is calculated. Position of every particle is then changed according to its speed, with the speed changed according to its previous speed, added to the speed with direction towards the position of the particle with the global best score, and also added with the speed with direction towards the position of the particle's personal best. In every iteration, the position of the particle with the highest score is noted. Iteration is stopped when the highest score doesn't change after a set amount of iterations.

4. RESULTS AND ANALYSIS

Optimization with PSO is successfully done with 2000 particles. PSO is stopped after the maximum score from the last 20 iterations is constant. Results from previous iterations show several patterns, depending on the weight of every component. This pattern is explained in Table 3.

Table 3: Different shapes found with various scoring weight settings.

Pattern	Weight	Note
The three bars coincide		The foot is lifted moments after the 3 bars coincide, with large angular acceleration

Large curvature of the foot		Wide foot, large phase angle
The foot is too wide		The total phase angle that touches the ground becomes very little
Best shape		Large phase angle over 3.14, no bars coincide.

This result is named Model 1 and is described in Table 4. Shape of Model 1 is shown in Fig. 9.

Table 4: Parameters of Model 1.

Parameter	Score
L12	60.6782
L24	47.3676
G	88.1454
Y1	-20.8691
X1	-12.9266

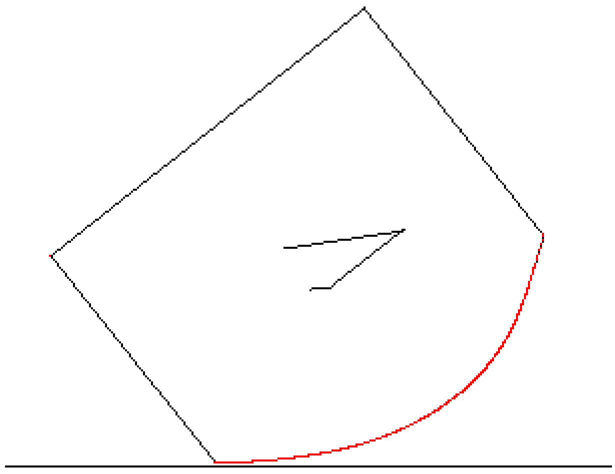


Figure 9: Model 1.

In Model 1, it is observed that:

- Phase angle that is in contact with the ground = 3.85 rad
- Distance travelled in one step: 12.5 cm with 1 cm crank
- Step height = 1.97 cm
- Linkage height = 10.9 cm
- Closest distance between point 1 and point 4 = 1.45 cm
- Lowest position of point 2 from ground = 6.68 cm

To observe the smoothness of the walk of this model, velocity over phase angle graph is made, which is shown in Fig. 10. Because the phase angle needed is only π rad, the feet curve is cut so it only touches the ground for just 3.14 rad. With this cut, the speed could be more uniform, which is shown with the orange part of the curve shown in Fig. 10.

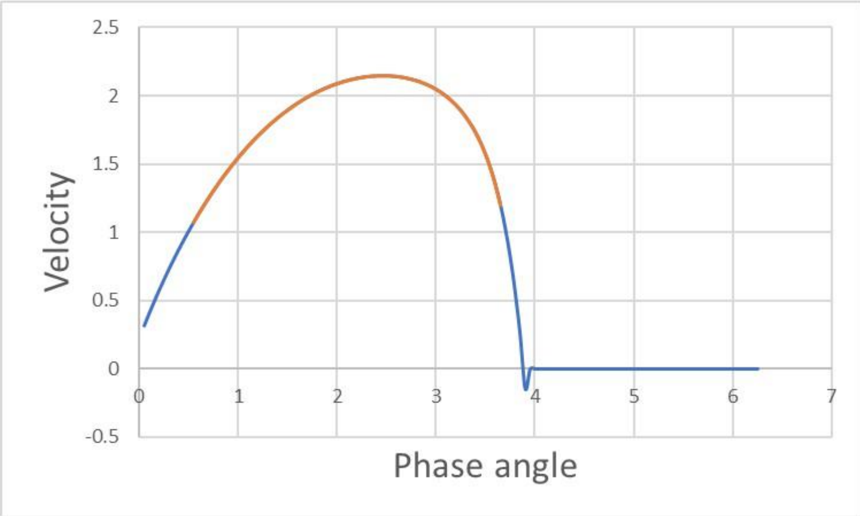


Figure 10: velocity to phase angle graph of Model 1. Orange line shows the most constant speed in interval 3.14 radian.

In early stages, it is found that the three rods can be in line at one moment in the movement. This could result in bending of the linkage when the constructed model is run. To overcome this, various approaches were taken. One of which is by calculating the instantaneous angular acceleration of bar 2-4, calculated by subtracting two last instantaneous angular acceleration. Angular acceleration is then used to calculate the scoring system with a certain power assigned to it. After angular acceleration (denoted with acc_angle) is calculated in the scoring, the problem of the three bars being inline is solved.

Implementation

Based on Model 1, a 3D design was made using Blender. The model has a crank radius (bar 3-4) of 10 mm. Overall size is 38 cm length, 25cm width, and 15 cm height. The total number of legs of the robot is 8, with 4 legs on each side. Front and rear leg pairs move synchronously with means of a triangle structure to translate the motor rotation to 2 other parallel axes. The motion source is a DC gear motor with 3-6V voltage specification for each side, powered from 4 alkaline AA batteries. The design is shown in Figure 11. The model was then fabricated by 3D printing from PLA material (Figure 12). Total printed mass is 350 grams.

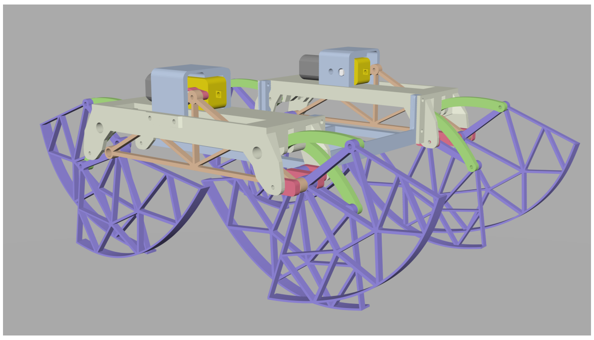


Figure 11: 3D design of the Rolling Step model.

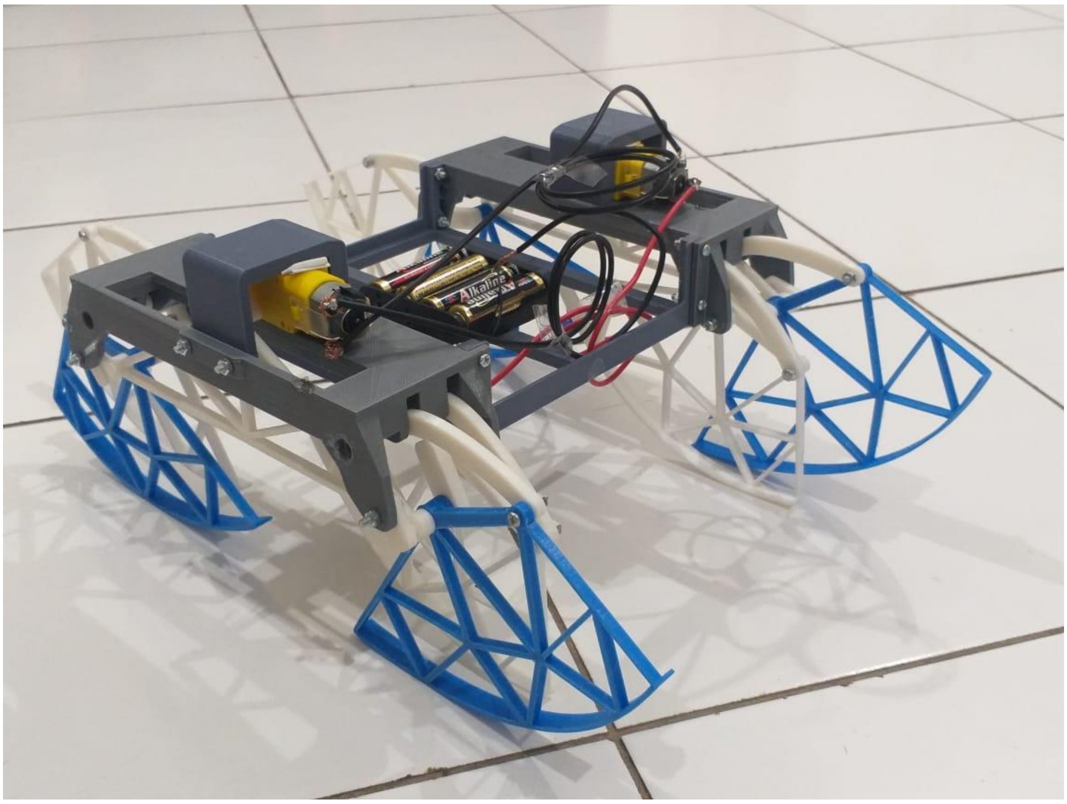


Figure 12: The Rolling Step model.

Performance

We tried to run the model on a hard, flat surface (ceramic tiles). It walks reasonably fast for its size without slipping. On dirt, it turned out that the current model is not capable of walking on dirt because the motor is not sufficiently powerful to overcome the high friction from the ground.

Future Works

For improvements, addition and usage of Arduino is possible to enable the robot to move in two dimensions by separately controlling left and right side like a tank. Increasing the power output is also necessary to enable the model to move in rougher terrains. The Rolling Step mechanism could also be applied to other linkages.

5. CONCLUSION

A simple 4 bar linkage which resembles rolling motion has been designed, manufactured, and tested. The design is proven to be capable of walking smoothly across flat, level terrain. However, the current model is not capable of walking on dirt because the dynamo is not sufficiently powerful to overcome the friction from the ground.

REFERENCES

1. Ingram, A.J. 2006. *A New Type of Mechanical Walking Linkage*. Disertasi. University of Johannesburg.

2. https://www.bostondynamics.com/legacy

3. Atmaja, Brahmanto Utama, Harianto, Ihyaudin. 2012. *Rancang Bangun Robot Quadropod Pendeteksi Halangan Dengan Menggunakan Logika Fuzzy.* Program Studi S-1 Sistem Komputer, STIKOM Surabaya.

4. Shigley, JE. 1960. *The Mechanics of Walking Vehicles*, Land Locomotion Laboratory Report No. LL-71, U.S. Army Tank-Automotive Command, Warren, Michigan.

5. Ziqiang Zhang, Bin Chang, Jing Zhao, Qi Yang, Xingkun Liu, 2020. *Design, Optimization, and Experiment on a Bioinspired Jumping Robot with a Six-Bar Leg Mechanism Based on Jumping Stability*, Mathematical Problems in Engineering, vol. 2020, Article ID 3507203, 23 pages. https://doi.org/10.1155/2020/3507203

6. Farhana Mohd Isharudden et al., *Design and Prototyping of a Motorized Legged Robot with Klann Linkage Mechanism*. International Journal of Emerging Trends in Engineering Research, 8(5), May 2020, 1941 – 1945. http://www.warse.org/IJETER/static/pdf/file/ijeter77852020.pdf

7. Sheba, Jaichandar Kulandaidaasan, Edgar Martínez-García, Mohan Rajesh Elara, Le Tan-Phuc. 2015. *Design and evaluation of reconfigurable Klann mechanism based four legged walking robot*. 1-5. 10.1109/ICICS.2015.7459939.

8. Nansai, Shunsuke, Mohan Rajesh Elara, Masami Iwase. 2013. *Dynamic Analysis and Modeling of Jansen Mechanism*. Procedia Engineering 64, 1562 – 1571.

9. Ghassaei, Amanda. 2011. *The Design and Optimization of a Crank-Based Leg Mechanism*. Thesis, Pomona College Department of Physics and Astronomy. https://amandaghassaei.com/files/thesis.pdf

10. https://demonstrations.wolfram.com/ChebyshevsLambdaMechanism/

11. *Plantigrade Machine - Mechanisms by Tchebyshev*. https://en.tcheb.ru/1

12. Wade Vagle, *Strider's Linkage Dimensions and Prototype Performance*. https://www.diywalkers.com/strider-linkage-plans.html

13. J. Kennedy and R. Eberhart, "*Particle swarm optimization*" Proceedings of ICNN'95 - International Conference on Neural Networks, Perth, WA, Australia, 1995, pp. 1942-1948 vol.4, doi: 10.1109/ICNN.1995.488968. https://ieeexplore.ieee.org/document/48896