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# Design and Modeling of Klann Mechanism-Based Paired Four Legged Amphibious Robot

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**ABSTRACT** The ability of the amphibious robot to walk on dry land and swim in the water motivates many researchers to explore the structural design strategies and control methods of the system. In this research, the paired four-legged amphibious robot is designed and modeled. The optimized Klann linkage mechanism is applied as the mechanism of the robot's leg. The kinematic analysis of the designed model is performed in SAM (Simulation and Analysis of Mechanisms) to study the motion trajectory of the system. The inverse dynamic analysis is used to obtain the driving torque of the actuator for the designed amphibious robot. The results demonstrate that the trajectory path of the lower part of the foot in the Klann mechanism is more horizontal than the four-bar mechanism and resulting in higher propulsion of the Klann mechanism than the four-bar mechanism. The simulation also reveals that the amphibious robot has the capability to maneuver and thus validate the ability of the designed model.

**INDEX TERMS** Amphibious robot, dynamic modeling, Klann mechanism, kinematic modeling.

## I. INTRODUCTION

Nature inspires to design and develop robotic platforms with improved functionality and performance. Biologically inspired amphibious robots take inspiration from living creatures because they possess excellent characteristics. One of the characteristics of amphibious creatures is locomotion in diverse environments like water, ground, and aerial. Insects such as gecko and basilisk lizard inspire extraordinary locomotion capabilities to develop robotic systems [1]. Robotists are exploring animals' designs and dynamic locomotion performance that can maneuver and adapt to a different environment. However, the robotic platforms developed for diverse environments have adaptive limitations, pose control challenges, and the nonlinear system behavior problems for these systems are non-trivial. These reasons have attracted the attention of researchers in this research area of amphibious robots.

In the past two decades, there has been significant development in propulsive mechanism for amphibious robot locomotion that exhibits excellent ability of locomotion on

multiple media surfaces like land, water, and the transition area between the media [2]. The amphibious robots have demonstrated potential locomotion capabilities, sophisticated unstructured land, and in the dynamic underwater environment [3]. The prospective application of these amphibious robots involves monitoring and locomotion in the complex environment that is difficult to maneuver in the areas like post-disaster are affected due to floods, cyclones, and landslides. The advanced applications involve dynamically changing underwater environments like deep-sea exploration, pipeline inspection, and structure monitoring. The reconnaissance and search and rescue operation also involves the locomotion capabilities of these mechanisms to change their locomotion at the transition region [4]. The challenging environment has motivated researchers in robotics to explore research avenues for locomotion and propulsive mechanism design and development of the amphibious robot.

Hybrid amphibious robots utilize a combination of mechanisms for locomotion on multiple media exploiting the advantage of each mechanism at different media. Li *et al.* [5] proposed an amphibious spherical robot that utilizes a leg mechanism for locomotion on land surface and a waterjet mechanism for propulsion on the water surface. Li *et al.* [6]

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modified the amphibious spherical robot leg mechanism by appending a passive wheel at each leg, increasing the mobility on the smooth land surface. The researchers studied kinematic and dynamic models in detail to optimize the design, increasing the performance metrics of amphibious spherical robots [7]. He *et al.* [8] presents multiple amphibious robot working in coordination that involves applications like box pushing. He successfully developed the father-son configuration of amphibious spherical robots. The other hybrid mechanism reported in the literature utilizes spherical configuration to increase the performance on the water. The propulsion on the water's surface is achieved by a hybrid mechanism involving a flywheel, propeller, and pendulum [2].

Legged amphibious robots are employed for maneuvering on irregular land terrains [9], and for running on the surface of water [10] or underwater swimming [11] or seabed crawling [12] with the same leg mechanism. Zhong *et al.* [13] investigate the stiffness effect on the motion performance of an amphibious robot. The amphibious robot locomotion mechanism utilizes flexible flipper legs. Variable stiffness allows the legs to change stiffness for arc-shaped legs for locomotion on land and a straight flipper for water locomotion. Klien *et al.* [14] discussed a locomotion mechanism that uses four thrusters for aquatic locomotion, and terrestrial locomotion employs four standard wheels. Zhong *et al.* [15] presents a novel design that utilizes transformable legs for locomotion on land and water. On land, motion is achieved using a rigid fan-shaped frame, and on water, propulsion is achieved using legs transformed to flippers. Xing *et al.* [16] proposed a novel design that incorporates a driving system consisting of mechanical legs with a waterjet thruster, lifting and supporting wheel mechanism for locomotion on water and land.

Insects and amphibious animals inspire walking and swimming mechanisms for traversing in these environments. Legged locomotion is a prominent motion strategy for maneuverability over irregular terrains and surfaces. Legged amphibious robots have gained momentum in recent years because of diverse gait patterns and maneuverability. Search and rescue operations employ legged amphibious robots [1]. The early study at the nanorobotics Carnegie melon university concentrated on the locomotion capabilities of legged lizards running on water and developed a robot platform that utilizes drag forces for propulsion. The developed robot had an advantage in running speed and energy consumption [17]. The robot developed by Karakasliotis *et al.* [18] takes inspiration from the salamander; the flexible body movement makes smooth locomotion in the water, and legs are utilized for walking on the ground. The robot inspired by the water strider utilizes surface tension to locomote on the water surface [4]. Yusof [19] presents an amphibious robot focusing on optimized path planing of amphibious robot using ant colony optimization technique and also, identifies walking gaits of amphibious robot to manueve on-land and underwater environment.

Mechanisms are widely employed as legs for amphibious locomotion. Kim *et al.* [20] uses the Klann mechanism with a tripod gait and spherical Styrofoam for buoyancy creation is utilized for a robot to work on the land and water, Leg mechanism with spherical Styrofoam allows the robot to operate in two environments. The experiment results demonstrate that on the land surfaces, the speed of the robot is higher, and aslo with an increase of frequency of the motor decreases pitching of an amphibious robot. Giri [21] utilized the Newton-Euler formalism dynamic modeling approach for open kinematic chain mechanism. Kinematic analysis of the three mechanisms and comparison of four-bar, Klann, and Watt-I, which closely resembles locomotion of basilisk lizard for stable and water running, is studied by [22]. Kim *et al.* [23] present the amphibious robot that utilizes the dynamic tail with a bang-bang controller that controls the yawing locomotion of the robotic platform. To calculate the yawing angle and position of a robot, the dynamic analysis utilizes the differential equation during steering operation. Komoda *et al.* [24] introduce the multi-body dynamic analysis approach to compare the performances of closed-loop linkages. The mechanism considered for analysis involves Klann, Chebyshev, and Theo-Jansen mechanism. Sheba *et al.* [25], [26] presents a reconfigurable design of four-legged amphibious robot. The reconfigurable links can generate five different gait locomotion configurations. However, to increase the propulsion and stability of the robot, both on land and water optimized mechanism modeling and its analysis have to be performed.

Thus a Klann based paired four-leg amphibious robot is designed and modeled to operate both on land and water. The robot uses the Klann mechanism as a leg mechanism of the robot because of closed planar mechanism simplicity design and control complexity that can operate for multimodal locomotion. The Klann mechanism is optimized and kinematically analyzed. The mechanism end-effector optimized trajectory reveals a close flat path at the lower part of the trajectory, parallel to the surface that maximizes therobot's propulsion, making it suitable for stable and fast running on aquatic and terrestrial surfaces. The Klann mechanism leg frequency can be increased for high-speed locomotion.

The paper is organized into four sections, section one introduces legged amphibious robots and associated literature work Section two describes the system integration of paired four-legged amphibious robots. Section three details forward kinematic and dynamic modeling of paired four-legged amphibious robots, and section four presents results and discussion. Finally, the conclusion and future work is discussed.

## II. SYSTEM ARCHITECTURE

### A. AMPHIBIOUS ROBOT SYSTEM STRUCTURE

The water running aquatic locomotion of the basilisk lizard inspires the design of the legged amphibious robot. Lizard utilizes drag force from the water for swimming and walking

legs for ground locomotion. In the current design architecture of a paired four-legged amphibious robot, the klann mechanism is used as a leg mechanism for locomotion. The system architecture comprises of four paired legs and main base. Figure 1 shows the CAD design amphibious legged robot. The robot consists of a total of eight legs arranged in pairs of four, two at the front and two at the rear end. The robot is designed to maneuver on land surface and water environments. The controller of the robotic system is arduino 3.0 robot and navigation of the system is provided by Global Positioning System(GPS) sensor Ublox Module. The gears speed and rotation is controlled using a ASLONG DC motor with specification of 80.96 as maximum torque and speed rating of 300 rpm. The actuation of each paired leg mechanism is achieved by DC motor conncted on each side through set of five gears.The gear ratio selected for the configuration is centre gear with 20 teeth center, middle 30 and rear end with 40 teeth.

The locomotion of amphibious robot is achieved using paired four legs attached to the base of the robot(B1). The design of amphibious robot incorporates fixed main base and paired two legs on each side controlled by a DC Motor(M). 3D solidworks in enviornment with motion study feature is utilized for modeling of amphibious robot. Figure1 illustrates the CAD design front view of paired legs on one side appended to fixed base using joints. Figure 1 demonstrated leg position with two links ends at the top of each leg appended to main base and at the bottom free link end scrolls over the land surface. The motor provides rotational motion attached to gears with the gear ratio of 1:4, where the gear is mounted or shifted from a ratio of 1:2 to 1:4. Figure 2 illustrates the gear shifts from gear (G1) to gear (G2) and from gear (G2) to gear (G3). Leg mechanism is combination of links arranged in klann linkage pattern. The minimum length of leg position estimates to 37.88mm at the initial position and maximum length covered by fully extended links is 116.33 mm.

The leg mechanism of amphibious robot exploits Klann mechanism as in Figure 5 that is a combination of two four-bar mechanisms. Klann-based mechanism behaves as leg mechanism replacing wheel emulating the gait of biological limbs motion. The Klann mechanism provides flexibility and enhances maneuvering performance on uneven terrain profiles by overcoming curbs, climbing steps of a staircase, and traversing unstructured areas presently inaccessible by a wheeled robot while not requiring a computing system to be controlled. Klann’s mechanism can change its linkage configurations to adapt its gait according to changes in the surrounding environment and generate foot trajectories. Klann’s mechanism in the legs achieves a path parallel to the ground and reconfigures the feet’ structure to favor the robot’s dynamics with buoyancy and drag forces. Figure 4 illustrates a four-bar mechanism schematic. The Klann mechanism model as in Figure 5 comprises of links  $L_{12}$ ,  $L_{24}$ ,  $L_{34}$ ,  $L_{25}$ , and  $L_{45}$ . Here,  $L_{12}$  is the link length between length



FIGURE 1. CAD design of paired four-legged amphibious robot leg position.

nodes 1 and 2. The link lengths and angle between the links determine the end effector position. The driving side parameters are  $L_{12}$  and  $L_{24}$ , and  $\beta$ ,  $L_{34}$ ,  $L_{45}$ , are the driven side parameters. The location of the driving crank pivot remains attached at the base link. The angle  $\theta$  and  $\delta$  are measured relative to the X-axis and the angles  $\phi$  and  $\psi$  are measured to the base link  $L_{12}$ . The coupler angle  $\beta$  is measured relative to link  $L_{24}$ .

$$k_{11} = \frac{r_b}{r_1} \tag{1}$$

$$k_{21} = \frac{r_b}{r_3} \tag{2}$$

$$k_{31} = \frac{r_1^2 - r_2^2 + r_3^2 + r_b^2}{2 * r_1 * r_3} \tag{3}$$

$$P = \cos(\theta_2) - k_{11} - k_{21} * \cos(\theta_2) + k_{21} \tag{4}$$

$$Q = -2 * \sin(\theta_2) \tag{5}$$

$$R = k_{11} - (k_{21} + 1) * \cos(\theta_2) + k_{31} \tag{6}$$

For the first four bar mechanism, the end effector position  $\theta_4$  is obtained solving equation 1 to 7.

$$\theta_4 = 2 * \text{atan}\left(\frac{-Q - \sqrt{Q^2 - 4 * P * R}}{2 * P}\right) \tag{7}$$

The output from the first four bar mechanism is used as input to obtain the second four bar end effector output parameters

$$\theta_3 = \text{atan}\left(\frac{B_y - A_y}{B_x - A_x}\right) \tag{8}$$

$$\theta_5 = 90 - \text{atan}\left(\frac{C_y - F_y}{C_x - F_x}\right) \tag{9}$$

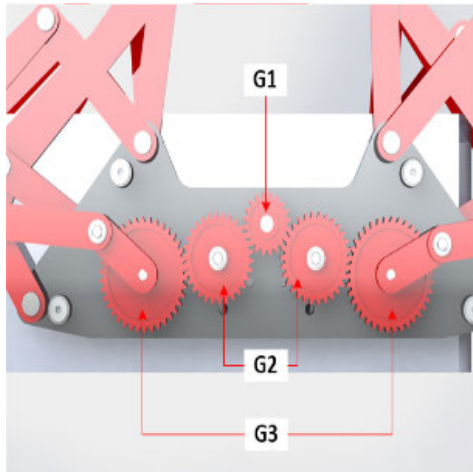


FIGURE 2. Gear position of paired four-legged amphibious robot leg position.

$$r_v = \sqrt{(C_x - F_x)^2 - (C_y - F_y)^2} \tag{10}$$

$$k_{12} = \frac{d_1}{r_v} \tag{11}$$

$$k_{22} = \frac{d_1}{r_6} \tag{12}$$

$$k_{32} = \frac{d_1^2 - r_v^2 + r_5^2 + r_6^2}{2 * r_6 * r_v} \tag{13}$$

$$P_1 = \cos(\theta_5) - k_{12} - k_{22} * \cos(\theta_5) + k_{32} \tag{14}$$

$$Q = -2 * \sin(\theta_5) \tag{15}$$

$$R_1 = k_{12} - (k_{22} + 1) * \cos(\theta_5) + k_{32} \tag{16}$$

The end effector position of second four bar position is as in equation 17

$$\theta_6 = 2 * \text{atan}\left(\frac{-Q_1 - \sqrt{Q_1^2 - 4 * P_1 * R_1}}{2 * P}\right) \tag{17}$$

### III. KINEMATIC AND DYNAMIC MODELING

#### A. KINEMATICS MODEL OF AMPHIBIOUS ROBOT

This section presents kinematic modeling and analysis of klann mechanism is employed as leg mechanism for robot inspired by basilisk lizard. Position, velocity, acceleration, end effector link lengths and orientation are represented as planar vector for the analysis. Figure 3 shows the general view of the Klann mechanism. The paired four legged amphibious robot forms a klann configuration with nine links appended to crank and rocker at the base link. The calculation of link length and joint angle is performed using equation 7, 17, 9 and 17.

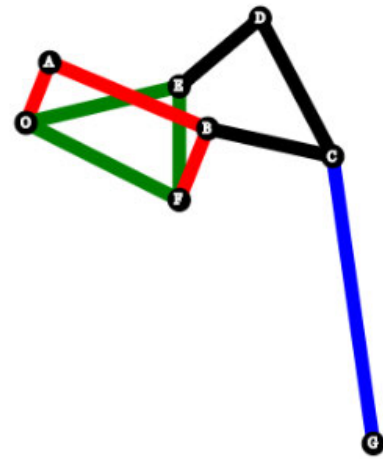


FIGURE 3. General view of Klann mechanism.

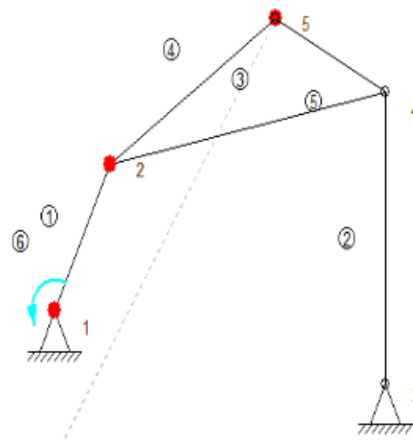


FIGURE 4. Schematic of a four bar mechanism.

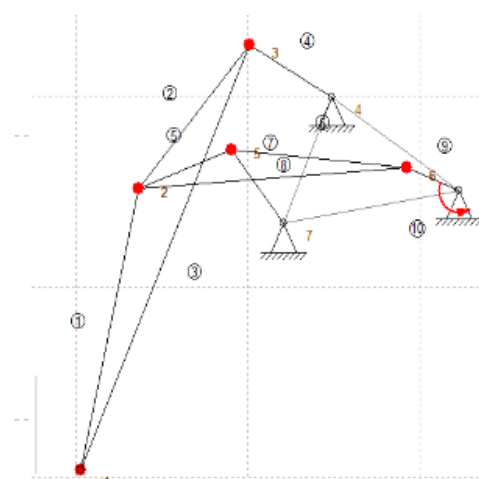


FIGURE 5. Schematic of a klann mechanism.

The leg mechanism is modeled as combination of two four bar mechanism, with first four bar mechanism mentioned as OABFO and the second mechanism as FCDEF. Here the link

TABLE 1. Parameters of Klann leg Mechanism.

Parameters	geometrical sides	Link length(mm)	Mass kg(x10 <sup>-3</sup> )
L <sub>68</sub>	OA	32.55	25
L <sub>56</sub>	AB	102.2	67
L <sub>26</sub>	AC	156.3	119
L <sub>34</sub>	ED	55.28	44
L <sub>23</sub>	DC	99.34	62
L <sub>12</sub>	CG	77.12	115
L <sub>25</sub>	BC	57.98	52
L <sub>13</sub>	DG	243.27	176
L <sub>57</sub>	BF	102.26	30
L <sub>48</sub>	OE		
L <sub>47</sub>	EF		
L <sub>78</sub>	OF		

FC is considered as imaginary. For formulation, OA = r1 AB = r2 BF = r3 BC = r4 CD = r5 DE = r6 FC = rv OF = rb

Here the notation L<sub>68</sub> specifies link length between nodes 6 and 8, as illustrated in Figure 5. L<sub>56</sub> is link length between nodes 5 and 6 and the remaining parameters also follow the same notation. The mass properties of each link length is mentioned in the table 1. The formulation first steps involve solving for both the four-bar mechanism parameters. The link lengths and angles are obtained as discussed and can be modified, for different trajectory patterns.

1) KINEMATIC ANALYSIS OF FOUR BAR AND KLANN MECHANISM

In [17] water-running robot utilizes four-bar mechanism which has four links forming one angle and five vectors, as shown in Figure 2, here L<sub>12</sub> is considered as the driving link. The foot of the leg mechanism is attached from the node 2, acting as end effector of the mechanism. The angle between links L<sub>42</sub> and L<sub>26</sub> is θ<sub>6</sub> and act as a divided vector. The position and velocity of the four-bar mechanism with end-effector attached can be calculated by summation of the vectors L<sub>13</sub> and L<sub>24</sub> as follows:

$$\vec{P}_{fourbar} = L_{13}e^{in\theta_{13}} + L_{24}e^{in\theta_{24}} \tag{18}$$

$$\vec{V}_{fourbar} = iL_{13}w_{13}e^{in\theta_{13}} + L_{24}w_{24}e^{in\theta_{24}} \tag{19}$$

The planar vector theory is utilized to perform velocity and position analysis of the leg mechanism. The position and velocity is calculated at the end effector node using Euler equation 20, and equation 21 gives the position and equation 22 gives the velocity in relationship with link lengths and joint angle between the links.

$$e^{in\theta} = \cos\theta_n + i\sin\theta_n \tag{20}$$

where θ<sub>n</sub> is the angle between the links L<sub>n</sub> and horizontal line, and n is number of vectors

$$\vec{P}_n = L_n e^{in\theta} \tag{21}$$

$$\vec{V}_n = \dot{P}_n = iL_n w_n e^{in\theta} \tag{22}$$

where  $\vec{P}$  is the position vector that define the position of the link,  $\vec{v}$  is the velocity vector that define the velocity of the link, and w<sub>n</sub> is the angular velocity of a link. The vector summation of P<sub>n</sub> and V<sub>n</sub> defines the end-effector position and velocity respectively.

Figure. 4 shows the Klann mechanism, it has combination of two consists four-bar mechanisms with 12 links, can be divided into three angles and ten vectors.

$$\vec{P}_{klann} = L_{84}e^{in\theta_{84}} + L_{43}e^{in\theta_{43}} + L_{32}e^{in\theta_{32}} + L_{21}e^{in\theta_{21}} \tag{23}$$

$$\vec{V}_{klann} = iL_{84}w_{84}e^{in\theta_{84}} + L_{43}w_{43}e^{in\theta_{43}} + L_{32}w_{32}e^{in\theta_{32}} + L_{21}w_{21}e^{in\theta_{21}} \tag{24}$$

The triangular ground geometry exists between nodes 4, 7, and 8, and the driving link of the mechanism is L<sub>68</sub> attached to the actuator. The end-effector is attached node 2 with link L<sub>12</sub>. The links L<sub>12</sub> and L<sub>23</sub> makes an angle θ. The same condition of four-bar mechanism applies to length of the triangular ground geometry which is fixed. For calculation of position and velocity of the end effector, the triangular line vector L<sub>47</sub> is fixed in the vertical direction and the vector summation of L<sub>84</sub>, L<sub>43</sub>, L<sub>32</sub> and L<sub>21</sub> is performed.

B. DYNAMIC MODELING

The dynamic modeling is performed using differential algebraic equations(DAE) we use the method of komoda et al. [24].For the dnamic modeling of klann mechanism the vectors q with 39 elements are defined as the generalized coordinates, placements and attitude angles are considered in this model. For the dynamic modeling 13 links are considered 12 links in original Klann mechanism and an end effector attached as an extension with a normalized stride length. In the present analysis a total of 39 (= 13 × 3) elements are obtained in the generalized coordinates.

$$q = [q_1^T, q_2^T, q_3^T, q_4^T, q_4^T, q_5^T, q_5^T, q_6^T, q_7^T, q_8^T, q_9^T, q_{10}^T, q_{11}^T, q_{12}^T, q_{13}^T]^T \tag{25}$$

The column matrix K(q) of kinematic constraint equation 27 gives first 38 elements. In the equation 27 for easy notion we use L<sub>1</sub> = L<sub>68</sub>, other notations as shown in Table 1 in sequential order,where t is time, and ω is the angular velocity of the crank in the mechanism. The calculation of Jacobian matrix φ<sub>q</sub> is performed using equation

$$\phi_q = \left[ \frac{\delta(\phi, t)}{\delta q} \right]_{39 \times 39} \tag{26}$$

Differential Algebraic Equation’s approach is utilized for the inverse dynamic analysis,since the system has only one degree of freedom, and the driving torque τ is

calculated using equation 28

$$\phi(q, t) = \begin{bmatrix} x_1 - l_1 \cos\theta_1 \\ y_1 - l_1 \sin\theta_1 \\ x_2 + l_2 \cos\theta_2 - x_1 - l_1 \cos\theta_1 \\ y_2 - l_2 \sin\theta_2 - y_1 - l_1 \sin\theta_1 \\ x_3 - l_3 \cos\theta_3 - x_2 + l_2 \cos\theta_2 \\ y_3 - l_3 \sin\theta_3 - y_2 + l_2 \sin\theta_2 \\ x_4 - l_4 \cos\theta_4 - x_3 - l_3 \cos\theta_3 \\ y_4 - l_4 \sin\theta_4 - y_3 - l_3 \sin\theta_3 \\ x_7 + l_7 \cos\theta_7 - x_6 - l_6 \cos\theta_6 \\ y_7 + l_7 \sin\theta_7 - y_6 - l_6 \sin\theta_6 \\ x_9 - l_9 \cos\theta_9 - x_8 + l_8 \cos\theta_8 \\ y_9 - l_9 \sin\theta_9 - y_8 + l_8 \sin\theta_8 \\ x_{11} - l_{11} \cos\theta_{11} - x_{10} + l_{10} \cos\theta_{10} \\ y_{11} - l_{11} \sin\theta_{11} - y_{10} + l_{10} \sin\theta_{10} \\ x_4 + l_4 \cos\theta_4 - x_2 + l_2 \cos\theta_2 \\ y_4 + l_4 \sin\theta_4 - y_2 + l_2 \sin\theta_2 \\ x_5 + l_5 \cos\theta_5 - x_2 + l_2 \cos\theta_2 \\ y_5 + l_5 \sin\theta_5 - y_2 + l_2 \sin\theta_2 \\ x_7 - l_7 \cos\theta_7 - x_4 + l_4 \cos\theta_4 \\ y_7 - l_7 \sin\theta_7 - y_4 + l_4 \sin\theta_4 \\ x_8 + l_8 \cos\theta_8 - x_3 - l_3 \cos\theta_3 \\ y_8 + l_8 \sin\theta_8 - y_3 - l_3 \sin\theta_3 \\ x_{10} + l_{10} \cos\theta_{10} \\ y_{10} + l_{10} \sin\theta_{10} \\ x_{12} + l_{12} \cos\theta_{12} \\ y_{12} + l_{12} \sin\theta_{12} \\ x_5 - l_5 \cos\theta_5 - x_{10} + l_{10} \cos\theta_{10} \\ y_5 - l_5 \sin\theta_5 - y_{10} + l_{10} \sin\theta_{10} \\ x_6 - l_6 \cos\theta_6 - x_{12} + l_{12} \cos\theta_{12} \\ y_6 - l_6 \sin\theta_6 - y_{12} + l_{12} \sin\theta_{12} \\ \theta_{11} - \frac{\pi}{2} \\ x_{13} - l_{13} \cos\theta_{13} - x_9 + l_9 \cos\theta_9 \\ y_{13} - l_{13} \sin\theta_{13} - y_9 + l_9 \sin\theta_9 \\ \theta_{13} - \theta_9 \\ \theta_1 - \omega t \end{bmatrix}_{39 \times 1} = 0 \quad (27)$$

$$\dot{\tau} = \frac{q'(M\ddot{q} - g)}{{}^{(d)}D - \dot{q}} \quad (28)$$

where  ${}^{(d)}D$  is the Jacobian of the driver constraints. It should be noted here that the array  $\dot{q}$  need not have to contain the actual velocity components of the system.

#### IV. RESULT ANALYSIS

The SAM software is utilized for the kinematic analysis of the Klann mechanism. The analysis aims to obtain the leg tracing, the foot locus, velocity and acceleration of the end effector. Additionally, the klann mechanism is compared with four-bar link mechanism in terms of motion trajectory, velocity and acceleration of the mechanism.

##### A. LOCOMOTION TRAJECTORY OF AMPHIBIOUS LEG

Legged robot locomote on the smooth and uneven surface of land. The locomotion cycle of leg undergoes stroke, stride and ride. The type mechanism chosen for the design of leg mechanism define the shape and coverage of legged robot over

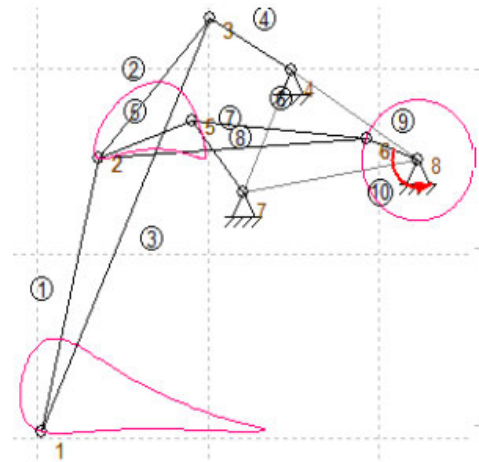


FIGURE 6. Motion trajectory of Klann mechanism.

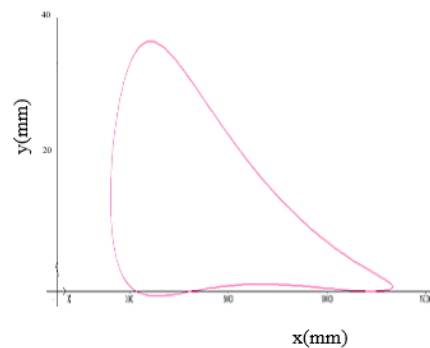


FIGURE 7. Stride length and height of the trajectory.

the surface. Klann mechanism with full trajectory tracking at the tip of end effector chosen for our design is shown in Figure 6. The trajectory path is close to pattern of amphibious leg. The stride length and height, and frequency of rotating cycle of defines the locomotion performance of leg mechanism on the land surface. The trajectory path is tracked at the node 1 of mechanism and driving trajectory of full cycle at node 8 where the crank connects to the main base of robot.

The stride shape facilitates gait identification of amphibious robot locomotion. Figure 7 demonstrates the stride shape with length 180 mm and height of the stride at 35 mm (swing and stance phase) of klann leg mechanism.

The complete cycle of 0-10 sec trajectory is obtained by varying the drive 0-360° of angle at the driving node 8 connected to the drive motor. Figure 13 shows trajectory path from T=1 to T=10 at time intervals two steps. The trajectory path is tracked for the shape of the stride and measures stride length and height with optimized link length and joint angles. The desired path for leg motion is triangular in shape that closely mimics leg's locomotion pattern of legged animals, as one side of triangle is parallel to surface it provide smooth locomotion performance on flat land surface. The trajectory path is obtained and compared with desired path, and the error is calculated. The error is utilized as objective

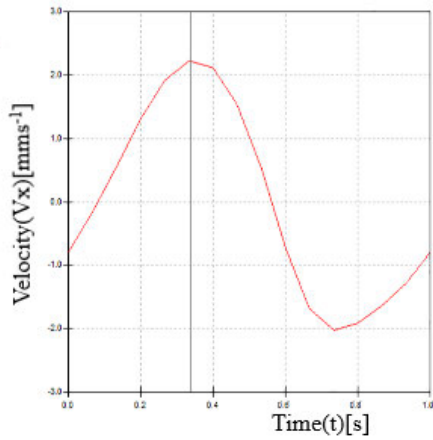


FIGURE 8. Velocity of four-bar.

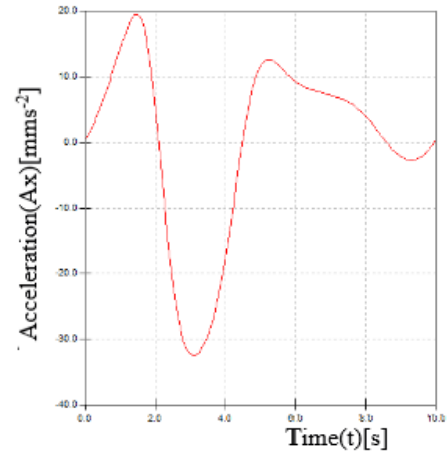


FIGURE 11. Acceleration of Klann mechanism.

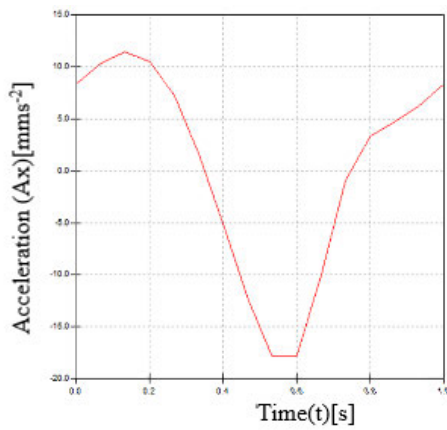


FIGURE 9. Acceleration of four bar.

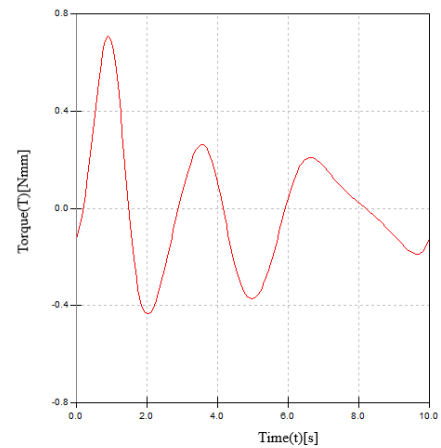


FIGURE 12. Driving torque of Klann mechanism.

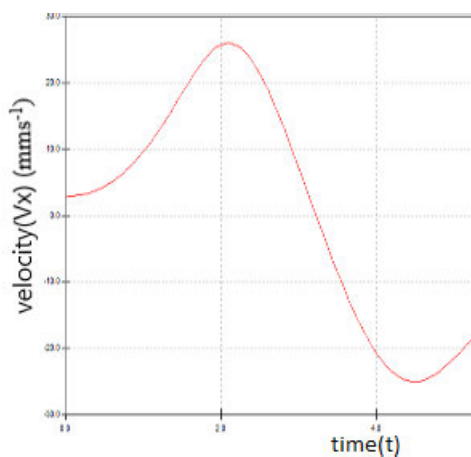


FIGURE 10. Velocity of Klann mechanism.

function for optimization. In the optimization process link lengths are considered as design variables to achieve desired trajectory path at the end effector. The optimization of mechanism provides optimized parameters as enlisted in Table 1.

The optimized trajectory pattern of klann mechanism is similar to the trajectory pattern of four bar mechanism. However, the klann mechanism trajectory pattern has advantage of lower part of the trajectory is more horizontal and acts parallel to the land surface allowing smooth and faster locomotion on the flat land surfaces. Four bar mechanism are utilized in application where the lifting forces are critical. The water stroke cycle requires lesser lifting forces, hence the four bar mechanism based leg mechanism finds advantageous in such applications.

**B. VELOCITY AND ACCELERATION ANALYSIS**

The velocity and acceleration of the four bar mechanism is shown in Figure 8 and 9. The kinematic analysis results demonstrate four bar mechanism has maximum velocity of  $0.227\text{ms}^{-1}$  and acceleration of  $0.833\text{ms}^{-2}$ . The velocity vector for the klann mechanism is calculated with respect to the point of origin by summing vectors  $V_k$  ( $k = 84, 43, 32,$  and  $21$ ). Figure 10 and 11 shows position and velocity results through kinematic analysis of klann mechanism.

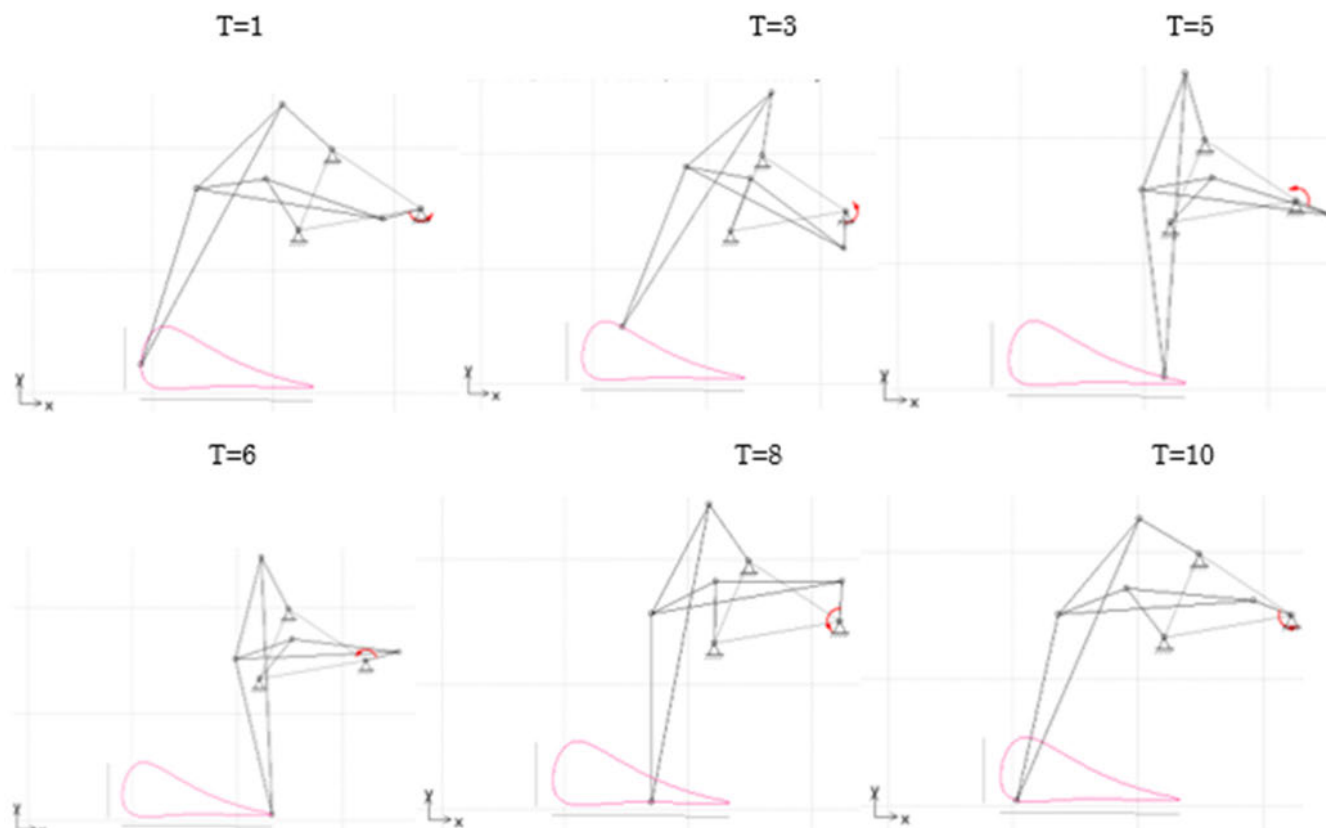


FIGURE 13. Trajectory of end effector at various time intervals of kinematic analysis.

The maximum velocity from simulation is  $0.52 \text{ ms}^{-1}$  and acceleration range is  $0.29 \text{ ms}^{-2}$ . The higher velocity of foot reduces the drag force on water and for the ground surface no slip is assumed so velocity of feet is same as velocity of the robot.

**C. TORQUE ANALYSIS**

Driving Torque is an important design parameter, its drive cycle effects the locomotion performance of leg mechanism effecting the frequency of stroke step and stride shape. The analysis of driving torque determines optimized swing cycle of leg mechanism reducing the energy consumption. Figure 11 demonstrates torque analysis of klann mechanisms reflecting the maximum and minimum torque requirement of the drive cycle at the driving node. The Figure 11 demonstrates the torque in the range  $-0.45$  to  $0.707$  the magnitude of amplitude is high increasing the energy consumption due to high lift forces of leg during swing phase. The klann mechanism torque waveform confirms the common property of closed loop linkage that the peak torque is generated during the swing phase at interval before lasting. The figure also reflects negative torque at the interval during stance phase that separates stance and swing phase.

**V. CONCLUSION**

The proposed klann mechanism based paired four legged amphibious robot is modeled for the locomotion on land and water surfaces. The designed robot has four feet in pair with Klann based mechanism as legs of the robot. kinematic analysis and simulation is performed using SAM. The Klann mechanism simulation results confirmed the trajectory is parallel to surface suitable for water running and ground traversing of the robot. In this work optimized Klann mechanism is utilized as leg mechanism to improve the speed performance of the amphibious robot. Kinematic analysis of klann based leg mechanism confirms that position and velocity of the end effector generates trajectory that is parallel to surface. The klann based mechanism in comparison with watt I and Cheychev mechanism are more efficient with same actuated frequency and foot velocity. The propulsion of the Klann mechanism is higher than the four-bar mechanism. However, due to smaller lifting forces of the four-bar mechanism has more efficient locomotion on the surface of water. The designed Klann leg mechanism velocity and acceleration of the proposed amphibious robot are analysed by simulation to validate the performance of the platform facilitating prototype development. Future studies will optimize the shape of the foot to increase the thrust and mobility performance on



the water. Also, the prototype development and its control strategy for paired four legged with klann mechanism will be investigated.

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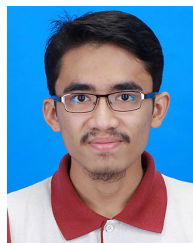
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