Modeling and Analysis of Novel Lizard Typed Robot

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***Abstract*—The purpose of this paper is to propose new type of a kinetic *chained* walking robot capable of walking with only single actuator. Legged robots are able to move across irregular terrains, however, have an issue on energy efficiency compared with other morphology. A bio-inspired approach often provides effective solutions, for example, a lizard is able to mainly walk by utilizing only twisting its waist. To mimic this characteristic by robotics, a robot consisting of four-bar linkage mechanism is proposed. This idea improves simplification of its locomotion analysis. In this paper, a kinematics of the robot is derived, and two important characteristics are analyzed in order to propose locomotion ability and effectiveness of the robot. The analysis results are verified via numerical simulation.**

***Index Terms*—bio-inspired robot, bilateration problem, kinematic analysis**

I. Introduction

Legged robots are always one of popular choice for robotics researchers due to their promulgation over traditional wheeled or followed automated stages on applications including mobility over irregular terrains [1, 2, 3]. Bartsch et al. have introduced the efforts in building up the "SpaceClimber 1", which is a bioinspired six-legged and vibrancy effective robot, for extraterrestrial surface investigation, especially for portability in lunar pits [4]. Estremera et al. have described the improvement of a hexapod robot "SILO-6" regarding crab and turning gaits, a characteristic landscape containing on uneven ground and humanitarian demining [5]. Moro et al. have proposed an approach of directly mapping a range of gaits of horses to a quadruped robot with the intention of generating a more realistic locomotion gait [6]. Reference [6] also has presented the utilize of kinematic motion primitives in generating stable and valid walking, trotting and galloping gaits that were demonstrated on a compliant quadruped robot. References [4]-[6] have shown that the robots developed were generally effective in mimicking the gait cycles of their biological counterparts, however, have possessed issues on high payload-to-machine-load ratio and high energy consumption. Several approaches developing energy-efficient walking machines have been reported. Reference [7] have shown that a set of rules are put forward towards improving energy efficiency in statically stable walking robots by comparing two-legged, namely, mammal and insect, configurations on a hexapod robotic platform. Reference [8] has presented an applied minimization criterion for optimizing energy efficiency in a hexapod robot with respect to each half of a locomotion cycle, especially walking on uneven terrains. Reference [9] has discussed two significant energy-efficient approaches towards determining optimal foot forces and joint torques for a six-legged robot.

Even though these literatures have focused on the energy consumption problem, the robots experimented have consisted of a series of links with multiple actuators to realize walking motion. Jansen, a Dutch kinetic artist, has proposed a novel closed kinematic chain consisting of an eight-bar linkage mechanism which requires actuation at only a single per leg through projecting internal cyclic motion into elliptical ones [10]. This kinematic chain has contributed to improving the energy efficiency issue. As another instance of researches to improve energy efficiency, a bio-inspired approach has been reported. For example, a team of College of Industrial Technology has found that a lizard mainly walks by utilizing only twisting its waist [11] and have analyzed the kinematics of a lizard typed robot [12]. In addition, the team has developed and demonstrated the lizard typed robot [13]. In our previous study, the dynamics of the lizard typed robot has been analyzed [14], and a robot capable of walking by only a single actuator has been developed [15]. [11]-[15] have been supposed to twist its waist as shown in Fig. 1. However, this walking pattern necessitates the robot to slip its toes. This feature decreases its energy efficiency and makes difficult to strict kinematic analysis because the analysis must include frictional characteristics, which vary considerably from place to place.

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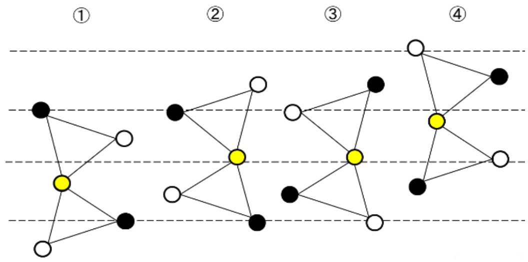

Figure 1. The kinematics model in the previous studies.

The purpose of this paper is to propose a new type of a kinetic chained walking robot capable of walking with only a single actuator. The robot is inspired by the lizard, however, it mimics the lizard with a four-bar linkage mechanism. Mimicking with this form allows walking without toe's slipping theoretically. This theoretical background provides simplification of a strict locomotion analysis because the robot can locomote without slipping. That is, the strict locomotion analysis can be accomplished due to its fixed support leg as a fixed link. A kinematics model of the four-bar linkage, i.e., a kinematics model of the robot is derived by solving a bilateration problem [16, 17, 18]. The model consists of two sub-model switched by the support leg. The derived kinematics model is analyzed from the side of view of both locomotion velocity and curvature. The analyses are the most basic characteristics for robot control as well as a robot design. In the locomotion velocity analysis, it is proofed that the velocity depends on the amplitude and frequency of an input angle as well as link length of the robot. In the curvature analysis, it is proofed that the robot turns with constant curvature by adding an offset onto the input angle. In addition, the proofs are verified via numerical simulations.

This paper is organized as follows: The bilateration problem is introduced in Section 2. In Section 3, the kinematics model of the robot is derived by solving the bilateration problem. In Section 4, the locomotion velocity and the curvature of the robot are analyzed including proofs of the relation between the input angle and the model parameters. In Section 5, the numerical simulations in order to verify the analysis result are performed. Section 6 concludes this paper.

II. Bilateration Problem

The bilateration problem consists in finding the feasible locations of a point, say P_k, given its distances to two other points, say P_i and P_j, whose locations are known. Then, according to Fig. 2, the solution to this problem, in matrix form, can be expressed as:

$$p_{ik} = Z_{ijk} p_{ij} \tag{1}$$

where $p_{ij} = \overrightarrow{P_i P_j}$ and

$$Z_{ijk} = \frac{1}{2 s_{ij}} \begin{bmatrix} s_{ij} + s_{ik} - s_{jk} & -4A_{ijk} \\ 4A_{ijk} & s_{ij} + s_{ik} - s_{jk} \end{bmatrix},$$

is called a bilateration matrix, with $s_{ij} = d_{ij}^2 = \|p_{ij}\|^2$, the squared distance between P_j and P_j, and

$$A_{ijk} = \frac{1}{4}\sqrt{\left(s_{ij} + s_{ik} + s_{jk}\right)^2 - 2\left(s_{ij}^2 + s_{ik}^2 + s_{jk}^2\right)},$$

the oriented area of $\Delta P_i P_j P_k$ which is defined as positive if P_k is to the left of vector p_{ij}, and negative otherwise. The interested reader is addressed to [16]-[18] for a derivation of (1) and its properties.

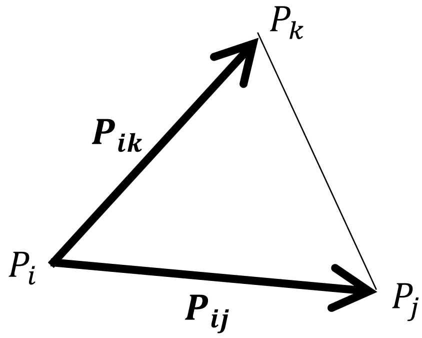

Figure 2. The bilateration problem.

III. Modeling

In this section, the kinematics model of the robot is derived by solving the bilateration problem. Utilizing the bilateration matrix provides to avoid deriving complex angle function consisting of function including another angle function.

Fig. 3 shows a schematic figure of the robot, and Table 1 shows definition of physical parameters. From Fig. 3, the robot possesses own local coordinate on a middle of p_{12}, O_r and middle of p_{34}, say O_r'. In addition, let $\theta_1(t)$, $\theta_2(t)$, $\theta_3(t)$ and $\theta_4(t)$ are relative angles between each link, and $\theta_b(t)$ is an absolute angle of p_{14}. $\theta(t)$ is defined as the input angle , i.e., the robot is controlled by decision of this function. The kinematics model of the robot consists of two model corresponding to different support leg, and is derived as follows: The model setting p_{41} as support leg is derived as *Model-1* first, and after that, the one setting p_{23} as support leg as *Model-2*.

TABLE I. Physical Parameters

Parameters	Notation	Value
Length of both P_1P_2 and P_3P_4 [m]	l	0.5
Length of both P_2P_3 and P_1P_4 [m]	d	1.0

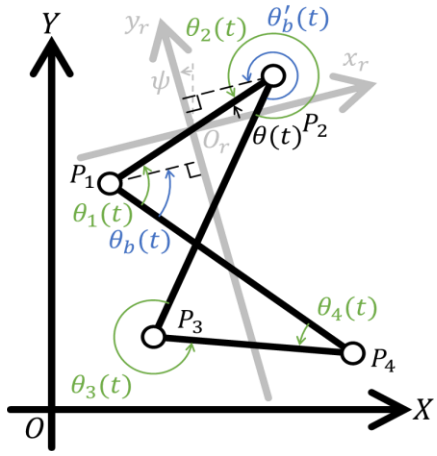

Figure 3. The schematic figure of the robot.

The Model-1 is derived. In this model, position of P_1 and P_4 are known since p_{41} is set as support leg. From Fig. 3, $\theta_b(t)$ is formulated as

$$\theta_b(t) = \cos^{-1}\left(\frac{l}{d}\cos\theta(t)\right) \tag{2}$$

Thus,

$$\theta_1(t) = \theta(t) + \theta_b(t).$$

By the law of cosines,

$$s_{24} = l^2 + d^2 - 2ld\cos\theta_1(t).$$

And, we obtain

$$p_{42} = Z_{412}p_{41}.$$

Also,

$$p_{43} = Z_{423}p_{42}.$$

Therefore, position of P_2 and P_3 are represented as follows:

$$P_2 = P_4 + p_{42},$$

$$P_3 = P_4 + p_{43}.$$

Solving P_1, P_2, P_3 and P_4 with respect to each $\theta(t)$ models the kinematics of Model-1.

Next, the kinematics of Model-2 is also derived. In this model, position of P_2 and P_2 are known since p_{23} is set as support leg. Theorem of the four-bar linkage mechanism provides

$$\theta_3(t) = \theta_1(t) = \theta(t) + \theta_b(t).$$

Hence,

$$s_{24} = l^2 + d^2 - 2ld\cos\theta_3(t).$$

And, we obtain

$$p_{24} = Z_{234}p_{23}.$$

Also,

$$p_{21} = Z_{241}p_{24}.$$

Therefore, position of P_1 and P_4 are represented as follows:

$$P_1 = P_2 + p_{21},$$

$$P_4 = P_2 + p_{24}.$$

Solving P_1, P_2, P_3 and P_4 with respect to each $\theta(t)$ models the kinematics of Model-2.

IV. Kinematics Analysis

In this section, the kinematics characteristics are analyzed. The characteristics are important bases for locomotion control as well as mechanical design in order to satisfy requirement specifications.

First of all, the input angle function $\theta(t)$ which is important basis as well is introduced. In this study, we define the input angle function as

$$\theta(t) = \alpha\sin(\omega t - \phi) + \beta \tag{3}$$

(3) is sinusoidal wave with bias, where, α is amplitude, ω is frequecy, $\phi(= \pi/2)$ is phase, and these parameters are tuning parameters. That is, a locomotion control of the lizard robot is on solving inverse problems of the parameters which realize desired locomotion. Following analyses are base of it, and are to solve direct problems. In addition, these are necessary for mechanical design satisfying required specifications. For following analyses, it is important that (3) is a simple periodic function. The velocity and the curvature seem vary continuously, however, possess same characteristics periodically. Thus, the analyses are able to be accomplished by periodical comparisons.

A. Locomotion Velocity Analysis

A first analysis is the locomotion velocity. Generally, the velocity is defined as traveling distance per unit time, however in this paper, we define the locomotion velocity as traveling distance per period. Thus,

$$v := f\Delta s,$$

where f and Δs are frequency of the input angle function and the traveling distance per period. By assuming $\beta = 0$ as early stage of this study, f and Δs is obained as follows:

$$f = \frac{\omega}{2\pi},$$

$$\Delta s = 2l\sin\alpha.$$

Finally, the locomotion velocity is formulated as

$$\boldsymbol{v} = \frac{\boldsymbol{\omega l}}{\boldsymbol{\pi}}\mathbf{sin}\boldsymbol{\alpha}. \tag{4}$$

From (4), the locomotion velocity depends on the parameters of the input angle function as well as link length which is the physical parameter of the robot. That means that the velocity can be tuned by the input angle function's parameters so that actuator's specification satisfies a required specification. Another means that the robot design influence maximum limit of feasible velocity. That is, (4) becomes an important index for the locomotion control as well as the mechanical design.

B. Curvature Analysis

A second analysis is the curvature. The turning locomotion generates as long as adding β which is non-zero, due to inequality of θ_b. We now proof that the robot turns with constant curveture by adding β with constant value. First, inequality of θ_b per half period by adding β with non-zero is proofed. After that, it is proofed that the inequality possess equality on first-half period and second-half period. Note that arguments i ($i = 0,1,2$) represent initial time ($t = 0$), half period time ($t = \pi/\omega$), one period time ($t = 2\pi/\omega$), respectively.

First, inequality of θ_b per half period by adding β with non-zero is proofed. In this case, we suppose to Model-1. $\theta_1(0)$ and $\theta_1(1)$ are follows:

$$\theta_1(0) = -\alpha + \beta + \cos^{-1}(C_0),$$

$$\theta_1(1) = \alpha + \beta + \cos^{-1}(C_1).$$

$$C_0 := \frac{l}{d}\cos(-\alpha + \beta)$$

$$C_1 := \frac{l}{d}\cos(\alpha + \beta)$$

Thus, variation of $\theta_1(t)$ during half period is

$$\theta_1(1) - \theta_1(0) = 2\alpha + \psi(1), \quad (5)$$

where,

$$\psi(1) = \cos^{-1}(C_1) - \cos^{-1}(C_0). \quad (6)$$

If the robot is moving straight forward, the y_r axis has to overlap on the one before half period, i.e., the variation of $\theta_1(t)$ has to equal to the one of $\theta(t)$ which equals to 2α. Thus, the robot is turning. In addition, (5) shows that the x_r axis rotates $\psi(1)$ rad from the x_r axis on the initial time, also y_r as well. Thus, the turning curvature from the initial time to the half period time is $\psi(1)$.

Next, it is proofed that the inequality of β possess equality on first-half period and second-half period. During second-half period, the link P_2P_3 is the support leg. In this case, we suppose to Model-2. $\theta_2(1)$ and $\theta_2(2)$ are follows:

$$\theta_2(1) = -\alpha + \beta + 2\pi - \cos^{-1}(C_0),$$
$$\theta_2(2) = \alpha + \beta + 2\pi - \cos^{-1}(C_1).$$

Thus, variation of $\theta_2(t)$ from half period to one period is

$$\theta_2(2) - \theta_2(1) = 2\alpha + \psi(2) \quad (7)$$

where,

$$\psi(2) = \cos^{-1}(C_1) - \cos^{-1}(C_0) \quad (8)$$

As in the case of (5), (7) shows that the robot rotates (8) rad from half period to one period. In addition, (8) equals to (6). Thus, the inequality of β possess equality on first-half period and second-half period.

The two proofs provide new facts: The robot is able to rotate by adding β, and its curvature is constant as long as β is constant. In addition, (6) and (8) indicate that the curvature depends on the parameters of the input angle function as well as ratio of link length.

Results of the two analyses are important for actual mechanical design, and open new possibility for optimal mechanical design.

V. Numerical Simulations

The analysis results are valid via the two numerical simulations. The simulations are performed by MATLAB 2018b. The physical parameters of the robot are shown in Table 1. The simulation time was 4 sec. The sampling interval was $\pi/(8\omega)$ sec. And, the parameters of the input angle function were as follows:

$$\alpha = \frac{\pi}{6},$$
$$\omega = 10,$$
$$\phi = \frac{\pi}{2}.$$

A first simulation is regarding to the locomotion speed. By setting $\beta = 0$, (4) is calculated as $v = 0.75$ m/s with Δs=0.5 m theoretically. Simulation results are shown in Fig. 4, Fig. 5 and Fig. 6. Note that marks are pointed per half period. From Fig. 4, the robot walks 3 m in 4 sec. Thus, the robot walks 0.5 m per period. From Fig. 5, the locomotion velocity of the robot is always 0.75 m/s. Also, Fig. 5 shows that the robot locomotes on straight line with periodic motion. This is also able to be found in Fig. 6.

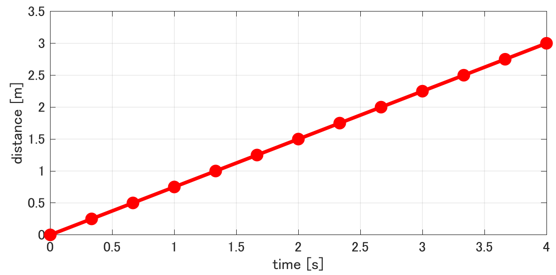

Figure 4. Time variation of walking distance.

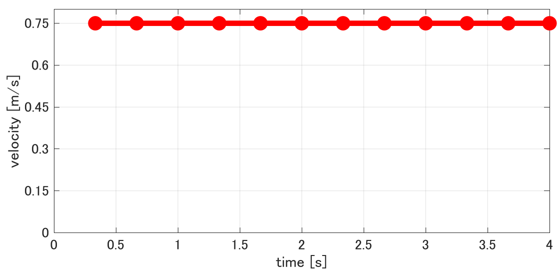

Figure 5. Time variation of locomotion velocity.

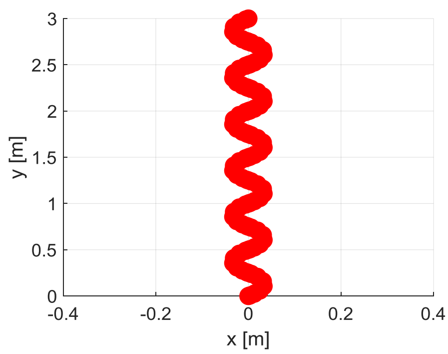

Figure 6. Trajectory of the robot.

A second simulation is regarding to the curvature. By setting $\beta = \pi/6$, (6) and (8) are calculated as 0.27 1/m theoretically. Simulation results are shown in Fig. 7, Fig. 8 and Fig. 9. Note that marks are pointed per half period. Fig. 9 clearly shows that the robot locomotes with turning. In addition, Fig. 7 shows that the robot turns about 3.3 rad in 4 sec, and its increasing rate is constant. From Fig. 8, the curvature of the robot is always constant on 0.27 m/s.

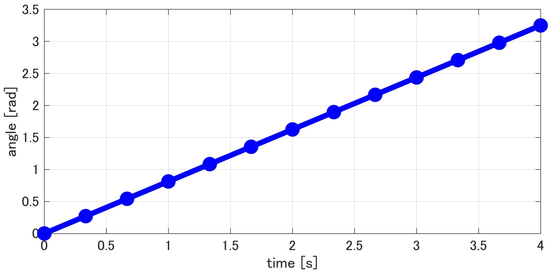

Figure 7. Time variation of the turning angle.

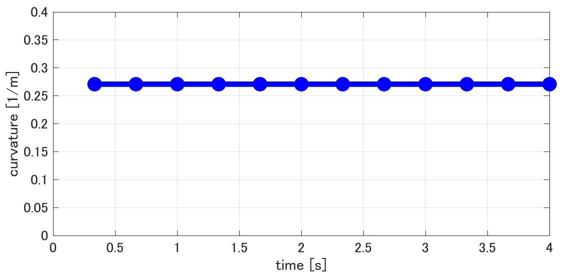

Figure 8. Time variation of the curvature.

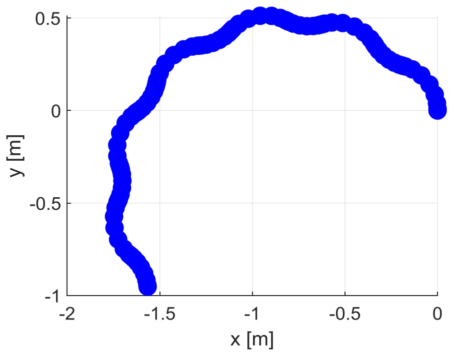

Figure 9. Trajectory of the robot.

Above two simulations prove that the kinematics analyses are validness, and the locomotion control and the mechanical design can refer the analysis results as most basic characteristics.

VI. Conclusion

This paper has proposed the new type of kinetic chained walking robot which is inspired from lizard. The lizard is capable of walking by mainly twisting its waist, i.e., it can locomote with one degree-of-freedom. That contributes highly energy efficiency. In the previous study, the kinematics model consisting of double triangle as shown in Fig. 1 has been adopted. That model always possesses issue on varied frictional characteristics. For this issue, the new type of kinematic chained model has been introduced in this paper. The model consists of four-bar linkage mechanism, and is also allowed to walk by single actuator as well. The novel characteristics of this model is to be able to walk without considering slipping theoretically. That provides simplification for the analysis. In this paper, the kinematics model of the new lizard typed robot has been derived first. The model has consisted of two sub model, and has derived by solving the bilateration problem. Second, the two kinematics characteristics have been analyzed. The first characteristic is the locomotion velocity. It has been proofed that the locomotion velocity depends on the parameters of the input angle function as well as length of the link. The second characteristic is the curvature. It also has been proofed that the curvature is constant as long as adding beta with constant value. The two characteristics has been verified via the numerical simulations. The analysis results provide the most basic characteristics of the robot, and will be absolutely necessary for the locomotion control system design as well as the mechanical design.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Shunsuke Nansai, Norihiro Kamamichi, and Hiroshi Itoh established the concept of this research; Shunsuke Nansai, Ryo Akai, and Yuki Ando analyzed the data; Shunsuke Nansai wrote the paper;

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