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Kinematic Analysis and Experimental Verification on the Locomotion of Gecko

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Abstract

This paper presents a kinematic analysis of the locomotion of a gecko, and experimental verification of the kinematic model. Kinematic analysis is important for parameter design, dynamic analysis, and optimization in biomimetic robot research. The proposed kinematic analysis can simulate, without iteration, the locomotion of gecko satisfying the constraint conditions that maintain the position of the contacted feet on the surface. So the method has an advantage for analyzing the climbing motion of the quadruped mechanism in a real time application. The kinematic model of a gecko consists of four legs based on 7-degrees of freedom spherical-revolute-spherical joints and two revolute joints in the waist. The motion of the kinematic model is simulated based on measurement data of each joint. The motion of the kinematic model simulates the investigated real gecko's motion by using the experimental results. The analysis solves the forward kinematics by considering the model as a combination of closed and open serial mechanisms under the condition that maintains the contact positions of the attached feet on the ground. The motions of each joint are validated by comparing with the experimental results. In addition to the measured gait, three other gaits are simulated based on the kinematic model. The maximum strides of each gait are calculated by workspace analysis. The result can be used in biomimetic robot design and motion planning.

Keywords: kinematic analysis, locomotion of gecko lizard, gait simulation, various gaits, workspace analysis

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1 Introduction

Sprawled-posture quadrupedal animals have an advantage over those with upright posture in their ability to adapt to various environments or in climbing a vertical wall, since their center of mass is close to the locomotor surface. Among sprawling quadruped animals, geckos are notable for their climbing ability on vertical surfaces. Therefore gecko's climbing ability on smooth vertical surfaces has been successfully validated through biological experiments[1]. And because it is an approach to develop legged robots that emulating motion and structure of biological creature, gecko-based biomimetic robots have been researched worldwide[2].

Research on gecko-inspired robots can be divided into two categories. The first category of research studies the adhesive ability of the gecko's foot, and the second adopts the quadruped motion of the gecko. Based on the investigation of structures of the gecko's foot[3,4], robots using a gecko-inspired adhesive pad have been proposed[5,6]. Unver *et al*. developed "Geckobot" that uses three servomotors, four adhesive footpads, and an active tail which is used to compensate the reaction force of the body[7]. Cutkosky *et al*. developed "Stickybot", which achieves adhesive force by controlling the tangential contact force of the directional adhesive pads[8,9]. Although these robots can climb sloped walls, they cannot climb various shaped walls since they are designed to move on a simple and flat surface.

Because kinematic analysis of a quadruped robot is important in gait planning, selection of kinematic parameters, and dynamic analysis, it has been widely investigated. Most of the kinematic analyses of quadruped robots have been performed by assuming the body and leg as a serial mechanism[10]. Because the joint angle errors can result in foot position errors, this approach cannot satisfy the condition that the foot should be fixed at a point when it is attached to the ground. To solve this

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problem, some researches have contemplated the body and legs attached on ground as a parallel mechanism. However, these methods have drawbacks. The method assuming that the body has only one orientation limits the body's motion from six Degrees of Freedom (DOF) to three DOF[11]; and the method considering all DOF costs a lot of computating time in solving the constraint equations[12].

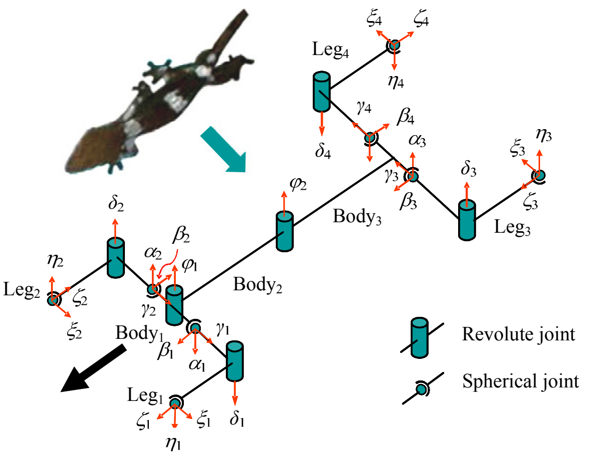
This paper proposes a kinematic analysis of the gecko model by considering it as a combination of serial mechanisms under constraints that a foot should maintain its position while contacting with the ground. The proposed method requires less computation time than previous researches, and does not restrict the motion of body. Furthermore, the research can make a contribution to the extension of biological experiments of gecko's motion because the motion of the kinematic model simulates the measured locomotion of the gecko. The motion of the gecko has been studied by researchers, but the results of such research show limitations[13–17]. The analysis in these researches did not consider the positional constraints of the attached feet, so the results cannot be applied to quadruped robots, especially to climbing quadruped robots.

The kinematic model in this study is composed of four legs based on 7- DOF Spherical Revolute Spherical (SRS) joints and two Revolute (R) joints at the waist, as shown in Fig. 1a. The legs attaching the surface and the other legs are considered as separate serial mechanisms. The kinematics of the constraints is computed without calculation of nonlinear simultaneous equations when two, three, or four legs are attached to the surface. The resulting motion of the kinematic model is validated by the experimental data of the locomotion of gecko. The gaits for different speeds and workspace are analyzed based on the kinematic model.

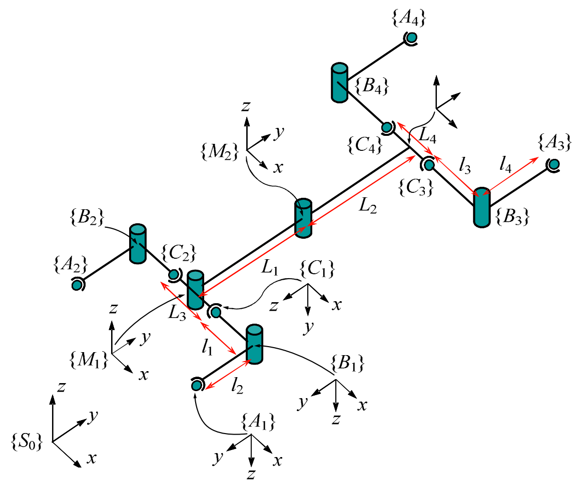
2 Kinematic analysis

2.1 Geometric configuration of the gecko model

Geometric configuration of the gecko model is shown in Fig. 1. Each leg consists of 7-DOF SRS-joints to simulate every motion of the leg. The Spherical (S) joints are denoted as (α_i, β_i, γ_i), (i = 1 to 4) and the R-joints are denoted as δ_i (i = 1 to 4), respectively. The main body is assumed to have two R-joints, which are denoted as φ_i (i = 1, 2), respectively. The two R-joints at the main body simulate the flexible transverse motion of the waist. Since most robots have one or no R-joint in their bodies, they have limitation in realizing the flexible transverse waist motion of the gecko.



(a) Joint angles



(b) Axes of moving frames and lengths of legs

Fig. 1 Geometric configuration of the gecko model: γ_i, β_i, α_i, ξ_i, ζ_i, η_i (i = 1 to 4) denote the rotation angles along the x, y, z axes in the {A_i} and {C_i}-coordinate, respectively. δ_i (i = 1 to 4) denotes the angles along z axis in the {B_i}. φ_i (i = 1, 2) denotes the rotation angle along the z axis in {M_i}-coordinate. The axes of {A_{2-4}}, {B_{2-4}}, {C_{2-4}} frames are not shown in the figure.

2.2 Assumption for calculation

The gecko model is assumed to be the combination of serial mechanisms when the two, three, or four legs are attached to the ground. For instance, when Leg$_1$ and Leg$_4$ are attached to the ground, the chain consisting of Leg$_1$ - Body$_1$ - Body$_2$ - Body$_3$ - Leg$_4$ is considered as one serial mechanism that completes a closed-chain, and Leg$_2$ and Leg$_3$ are considered as another serial mechanisms that makes an open-chain.

2.3 Methodology of kinematic analysis

The kinematic analysis is completed in three steps.

Firstly, the posture of the kinematic model is determined with respect to the end point (A_i), giving the joint angles except ζ_i, η_i, ξ_i to the gecko model by considering the whole model as a serial mechanism. Secondly, to determine the position and posture of the kinematic model with respect to the global frame S_0, (shown in Fig. 1) place A_i of one leg on the point of the previous moment, and place other legs that should be attached to the ground on close positions to the points of the previous moment. Due to the errors of joint angles, the feet associated with these legs cannot be placed on the points of the previous moment exactly through this step. Finally, adjust the joint angle data to satisfy the constraint conditions that maintain the position of the contacted foot on the surface. The procedure is detailed as follows.

2.3.1 Inserting joint angles data

This procedure aims to simulate the geometric configuration of the gecko model by assuming the model as a serial mechanism. For all joint angles except ζ_i, η_i, ξ_i (i = 1 to 4), the posture of each point A_i, B_i, C_i (i = 1 to 4), and M_i (i = 1, 2) in the A_1 or A_2 frame are calculated by using Homogeneous Transformation Matrices (HTM). Joint angles ζ_i, η_i, ξ_i are not directly used as input data because their errors can propagate to all links. These angles are determined in the next steps. The gecko model is modified to include the exact measured joint angles in free space, as shown in Figs. 2b and 2f. In the next step, the model is changed such that it is placed on the ground to simulate the locomotion of the gecko.

2.3.2 Determining the position and orientation of the model

The position and orientation of the kinematic model at the current time is determined in a global frame S_0 based on the posture of the previous time. Also, the position and orientation of the main body is selected iteratively by using the data of the model of previous time.

Details of the procedure and the results are shown in Fig. 2 and Fig. 3. There two states of the calculations: in the first state two feet are attached to the ground, and in the second state three or four feet are attached to the ground. In Fig. 2 and Fig. 3, the dashed line denotes the posture at the previous time, and the solid line denotes the posture at the current time, respectively. A_i' (i = 1 to 4) denotes the position of a foot at the previous time, and A_i (i = 1 to 4) denotes the position of a foot at the current time, respectively. $\hat{z}_{M_2}$ and $\hat{z}_{M_2}^{\text{Exp}}$ denote the current z-axis of M_2 from the kinematic model and current z-axis of M_2 from the experimental result, respectively.

Figs. 2a to 2e explain the procedure of the first state, two feet being attached to the ground. We assumed that Leg_1 and Leg_4 are attached to the ground. First, in the kinematic model, which is generated by the measured joint angles in Fig. 2b, A_1 is placed to be coincident with A_i' for the base point (see Fig. 2c). Then, A_4 is placed on the $\overline{A_1'A_4'}$ based on the calculated angle between $\overline{A_1'A_4'}$ and $\overline{A_1A_4}$ (see Fig. 2d). Finally, the model is rotated about $\overline{A_1'A_4'}$ to match $\hat{z}_{M_2}$ with the measured $\hat{z}_{M_2}^{Exp}$ (see

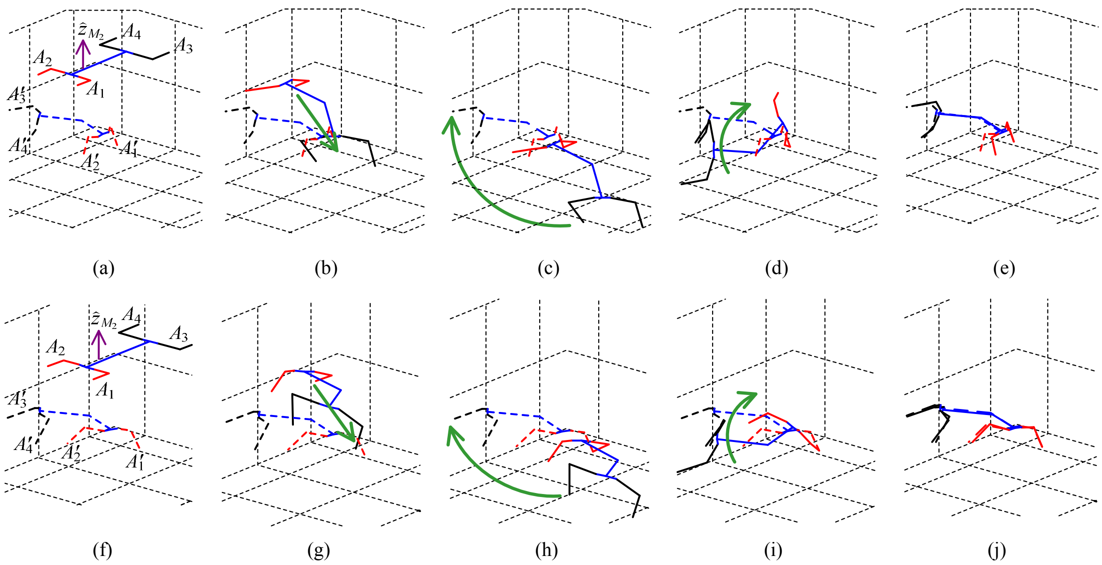


Fig. 2 Iterative procedure of the kinematic analysis: figures (a) to (e) explain the model when two feet are attached on the ground, and figure (f) to (i) explain the model when three feet are attached on the ground.

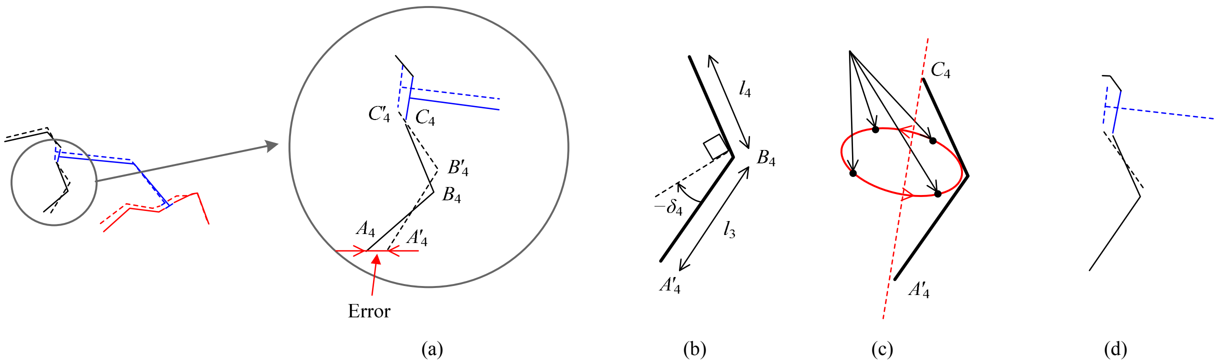


Fig. 3 Compensating joint angle error: (a) Error of A4 position; (b) Relationship between δ_4 and lengths of links; (c) Possible positions of B_4; (d) Result of compensated joint angle.

Fig. 2e). Therefore, the posture of the model can simulate an upright posture with two attached feet on the ground.

The model of the second state, three feet being attached to the ground is shown in Fig. 2f to 2i. We assumed that Leg$_1$, Leg$_3$, and Leg$_4$, are attached to the ground. The procedure that places A_1 to A_i' (see Fig. 2h) and A_4 on the $\overline{A_1'A_4'}$ (see Fig. 2i) is exactly the same as the procedure of the first state. As shown in Fig. 2j, the resulting model is obtained by rotating the model about $\overline{A_1'A_4'}$ until A_3 is placed on the plane that contains A_1', A_3', and A_4'.

At the moments when the attached legs are detached, or the free legs are attached to the ground, the proposed method can be applied successfully by switching the calculation algorithm. When one of two diagonal legs (e.g., Leg$_1$ and Leg$_4$) is always attached to the ground during movement, the switching algorithm simply changes the procedure between Figs. 2d to 2e and 2i to 2j for the detaching or attaching process.

However, due to the errors of the joint angles and constraints of the leg lengths, the calculated points of the feet, except A_1, have errors in their positions. The error will be compensated by adjusting the joint angles.

2.3.3 Modifying the joint angle data to attach feet

Due to joint angle errors, the contact points of the feet on the ground of the current posture do not coincide with those of the previous one. The positions of the attached feet should be such that the feet stay in one position to simulate the exact locomotion of the gecko; therefore, the process that compensates this error is essential for kinematic analysis.

The methods for the error compensation process are explained in the case of A_4, and the other cases can be solved by the same process. The posture of kinematic model when there is error in the position of A_4 is shown in Fig. 3a. The first step of the method is to place A_4 to A_4', to match the position of the attached foot. Then, δ_4 is determined uniquely by the geometric constraints of l_3, l_4, and $|\overline{C_4A_4'}|$ as follows (see Fig. 3b):

$$\delta_4 = \pm\cos^{-1}\left(\frac{l_3^2 + l_4^2 - \|\overline{C_4'A_4}\|^2}{2l_3l_4}\right) + 90^\circ \tag{1}$$

However, α_4, β_4, and γ_4 have infinite solutions since the legs can rotate freely along $\overline{C_4A_4'}$. Among the infinite solutions, a solution that gives the smallest difference from experimental angle data should be selected as the criterion (see Fig. 3c):

$$\min |\alpha_4 - \alpha_{4,\text{measured}}| + |\beta_4 - \beta_{4,\text{measured}}| + |\gamma_4 - \gamma_{4,\text{measured}}|, \tag{2}$$

where $\alpha_{4,\text{measured}}$, $\beta_{4,\text{measured}}$, and $\gamma_{4,\text{measured}}$ denote the measured angle by experiment. Consequently, the resulting posture of the leg is determined as shown in Fig. 3d.

As explained, feet positions (A_i (i = 1 to 4)) can be placed on the positions of previous movements by simply modifying joint angles, and so the proposed method can be applied to climbing robot where slip of foot is one of the most important issues. And also this method has relatively faster in calculation than the methods adopt numerical iterations, and so it provides a benefit in real time applications.

The proposed methods also can be applied to the case of three or four feet attachment. Since the methods consider the legs independently, it can compensate the error of each leg one by one for any case. Using this method the proposed kinematic model can satisfy the constraints of the positions of feet and the geometric parameters, and can minimize the error of the experimental results.

3 Experimental verification of the gecko model

This section presents the experimental validation of the kinematic model. The procedure and results of the experiment are presented, and the simulation results are discussed.

3.1 Measurement of joint angles

We used the crested gecko (*Rhacodactylus ciliatus*), and the body and leg lengths are given in Table 1. The meanings of each symbol have been presented in Fig. 1b. Video analysis has been widely used to measure the movement of the animals[18], in this experiment the locomotion of the gecko in the horizontal plane was measured using three camcorders (Sony DCR-TRV75, 30 frames per seconds). The horizontal motion of the gecko is investigated and analyzed. Since the moving direction of the gecko does not affect the kinematic analysis, therefore, the analytical method can be used to analyze the locomotion of vertical climbing[19]. One camcorder in the z-direction measures the x- and y-directional positions of the joints, and two camcorders in the x- and y-direction measure the z-directional positions of the joints, respectively. The positions of the joints were marked with white color and the measured position data of the joints are extracted from the image files manually using a CAD program.

Table 1 Geometric lengths of gecko (mm).

	Main body			
Symbol	L_1	L_2	L_3	L_4
Length	25	25	10	10
	Fore legs		Hind legs	
Symbol	l_1	l_2	l_3	l_4
Length	12	15	15	15

Totally, five data set of one cycle of repeated locomotion are acquired from several experiments. By using the position data of each joint, each angle of α_i, β_i, γ_i, δ_i (i = 1 to 4), and φ_i (i = 1, 2) was calculated from the inner and outer product of each directional vector. Among the five angular data, we selected one representative motion of one repeated cycle that had the most similar data to the average of the five experiments, as shown in Fig. 4. The angular data show symmetric shape along the middle point (around 0.3 sec) since gecko's motion of one cycle can be divided into the former half cycle and the latter half cycle and they are bilaterally symmetric. During the former half cycle, the gecko steps forward with its left foreleg and right hind leg, and during the latter half cycle, it steps forward right foreleg and left hind leg.

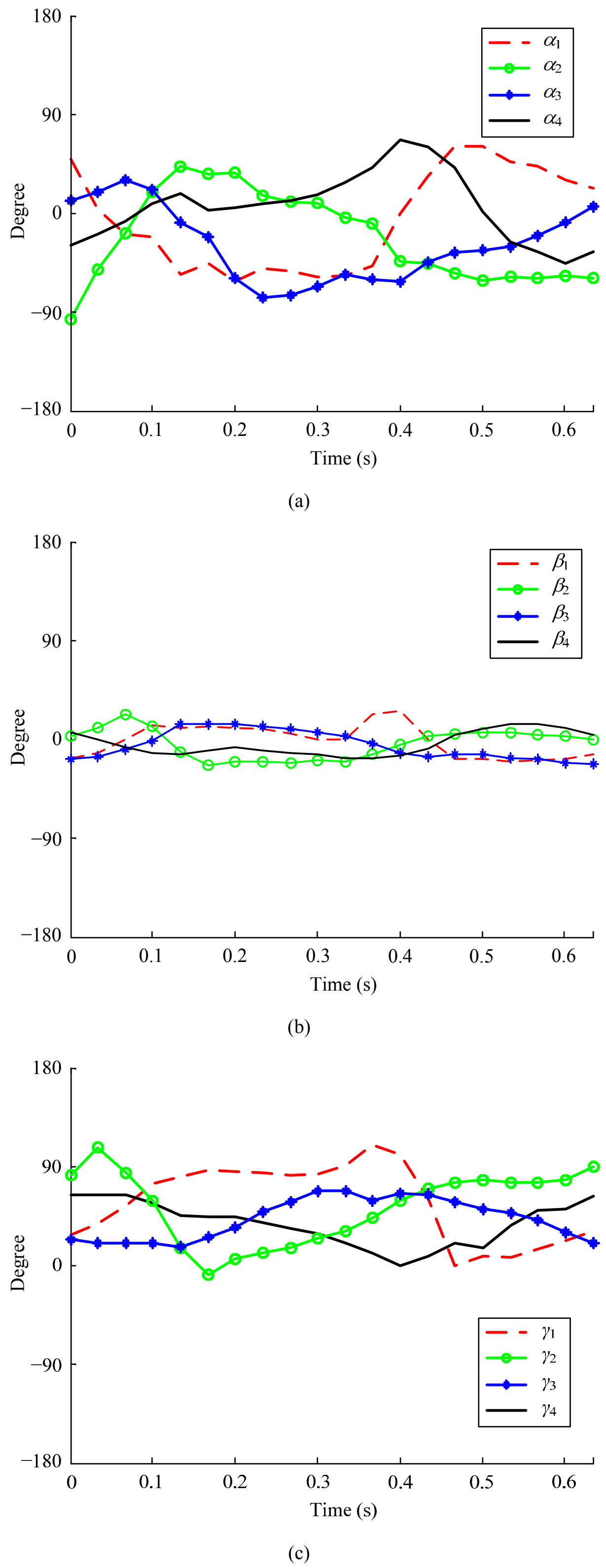
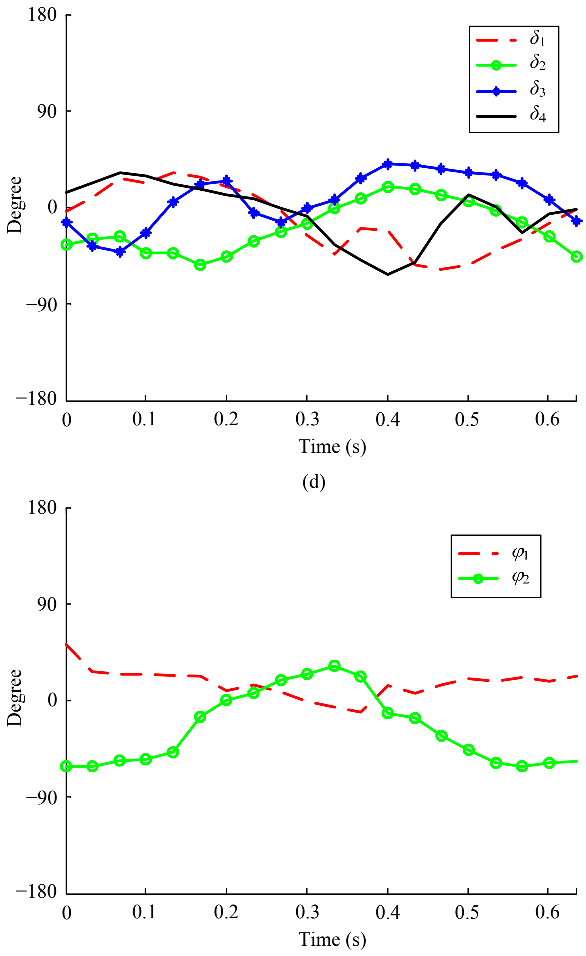


Fig. 4 Experimental joint angle data of the representative motion of the gecko.



(e)

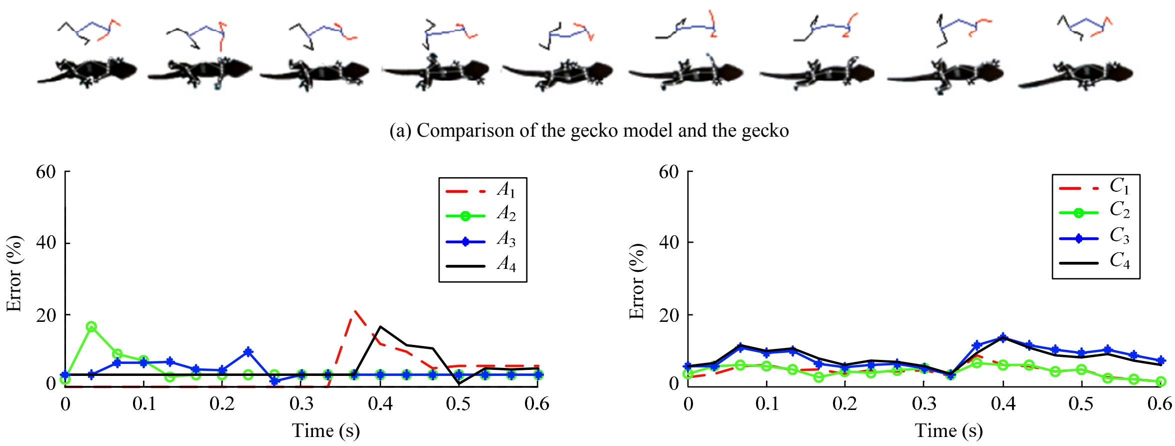
Fig. 4 Continued.

3.2 Validation of the kinematic model

The measured data in Section **3.1** were used to simulate the locomotion of the gecko based upon the kinematic model. The data of one cycle of gait consists of twenty images, in which ten measured images are used to simulate one cycle of gait, and the other ten images are used for verification. The posture for each of the ten kinematic models is calculated by the procedure given in Section **2**. The posture among the discrete kinematic models is generated by linear interpolation of the angle data.

The result of the comparison between the kinematic model and the measured images is shown in Fig. 5a. As shown, the upper kinematic model (solid line) can follow the posture of the images (dash line) through one cycle. The resulting eight joint positions of the kinematic model, A_i and C_i (i = 1 to 4), are compared with data from a total of twenty images. A_i and C_i are selected as the representative variables, since A_i indicates the points of the feet and C_i show the end points of the main body.

The error in the kinematic model is shown in Fig. 5b. The average error of A_i is measured as 4.29 % and the maximum error is measured as 21.25 %. The maximum error is measured in detaching the legs from ground since the kinematic model does not have links of feet. The average error of C_1 and C_2 is 4.31 % and the average error of C_3 and C_4 is 8.14 %, and the maximum error of C_i is 13.75 %, which is relatively smaller than the maximum error of A_i. The error of the hind legs is larger than the error of forelegs because while gecko has approximately twenty joints in its body, there are only two rotational joints in body of kinematic model. We can conclude that the simulation result via the proposed methods is well coincident with the experimental result, and mostly the error comes from experimental set up and modeling assumption.



(b) Distance error of the gecko model of one cycle

Fig. 5 Verification of the gecko model's motion: Error = (Distance between gecko's point and gecko model's point)/(Stride of one cycle) × 100 %.

We can consider two solutions to reduce the errors; adding one more link to each foot, and adding more joints to the waist. However, the two solutions also have a drawback in realization of robot design. Since the designed robot with more joints needs more actuators on its feet and waist, it will become heavy and hard to control. From the biological point of view, the two solutions can work to reduce the errors, and so one can get more accurate result with the model with more joints by following the proposed kinematic method.

4 Application of the kinematic model

This section describes the application of the kinematic model. Various gaits, including the measured gait are simulated based on the kinematic model and experimental data. Workspaces when two, three, and four legs are attached to the ground are calculated, respectively, and the maximum stride of each gait is determined from the workspace analysis.

4.1 Simulation of various gait types

Gecko changes its gaits according to its speed of movement. We can consider three options to increase the speed: longer stride, faster angular velocity of joints, and changing gait patterns. In previous research, it has been investigated that the gecko lizard does not change its stride length to increase speed in a same gait pattern[19], but the lizard achieves high speed motion by two solutions: maintain a specific gait and increase the angular velocity of the joints, or use several gaits in accordance with speed. From a practical point of view, it is necessary to use various gaits, considering the efficiency and capacity of the actuators. Therefore it is necessary to analyze various gaits of the gecko.

Before simulating various gaits of the gecko, the gaits must be named and defined. Since motions of the former half cycle and the latter half cycle are bilaterally symmetric, gaits can be named according to the number of attached legs on the ground for the half cycle. The starting point would be the maximum number of legs attached on the ground, and so, the measured gait is named as the 4-3-2-3 gait. That is, during the half cycle, gecko placed four legs on the ground and then three, two and three legs attached on the ground in sequential order. We investigate the gecko's gait in the order of speed as the 4-3-4-3 gait, 4-3-2-3 gait, 4-2 gait, and 2-0 gait. By using the measured data of the 4-3-2-3 gait, we can generate other three gaits, as shown in Figs. 6a, 6c, and 6d, respectively. The feet with dots indicate the attached feet on the ground. We set the standard angular velocity of the legs based on the measured 4-3-2-3 gait, which is shown in Fig. 6b. The unmeasured posture in the 4-3-4-3 gait is generated by the assumption of symmetry, and the jumping time in the 2-0 gait is assumed as one tenth of the attaching time based on previous research[15]. The average speeds of pint M_1 (see Fig. 1b) are set to 2.51 m·min^{-1}, 4.82 m·min^{-1}, and 6.41 m·/min^{-1} for the 4-3-4-3, 4-3-2-3, and 4-2 gaits, respectively. The speed of the 2-0 gait cannot be determined, since it changes during a jump motion.

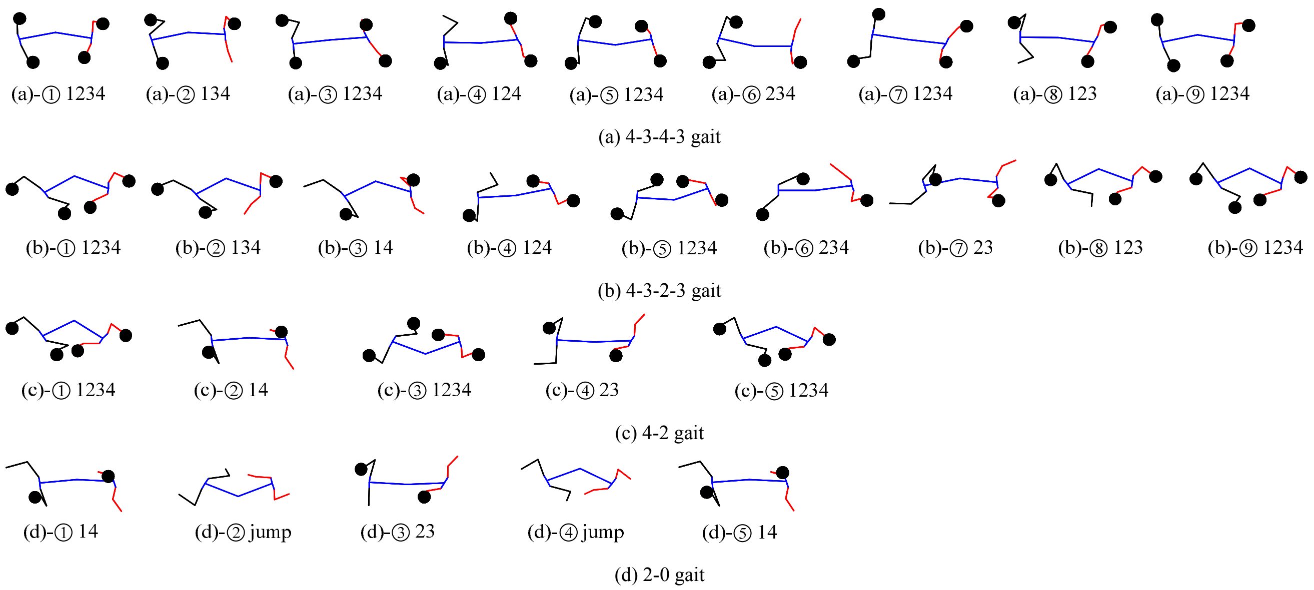


Fig. 6 Generated various gait types by using the kinematic model (top-view).

Table 2 shows average speed of point M_1 and average angular velocities α_i, β_i, γ_i, δ_i, φ_i of all joints during the locomotion of each gait. Interestingly, the average angular velocity of of 4-2 gait is smaller than that of 4-3-2-3 gait, even though the speed of point M_1 in 4-2 gait is faster than that of 4-3-2-3 gait. We can analyze that the feet moves longer distance to step on ground frequently during 4-3-2-3 gait, and so the angular velocity of joints should be larger than that of 4-2 gait. This result indicates that changing gait pattern is more efficient way to change the speed of body than changing angular velocities of joints.

Table 2 Average speed of M_1 and average angular velocities α_i, β_i, γ_i, δ_i, φ_i of all joints

Contents	4-3-4-3 gait	4-3-2-3 gait	4-2 gait
Average speed of M_1	2.51 m·s^{-1} 52 %	4.82 m·s^{-1} 100 %	6.41 m·s^{-1} 133 %
Average angular velocities	172.79 rad·s^{-1} 49 %	353.27 rad·s^{-1} 100 %	268.95 rad·s^{-1} 76 %

4.2 Workspace analysis and maximum stride

The x-y planar workspace is calculated by using the kinematic model. We define the workspace as the position where point M_1 can reach. The overall workspace consists of partial workspaces. Partial workspaces are determined according to which legs are attached and where the legs attached on the ground. For instance, the overall workspace for half cycle of the 4-3-2-3 gait is calculated by summing four partial workspaces.

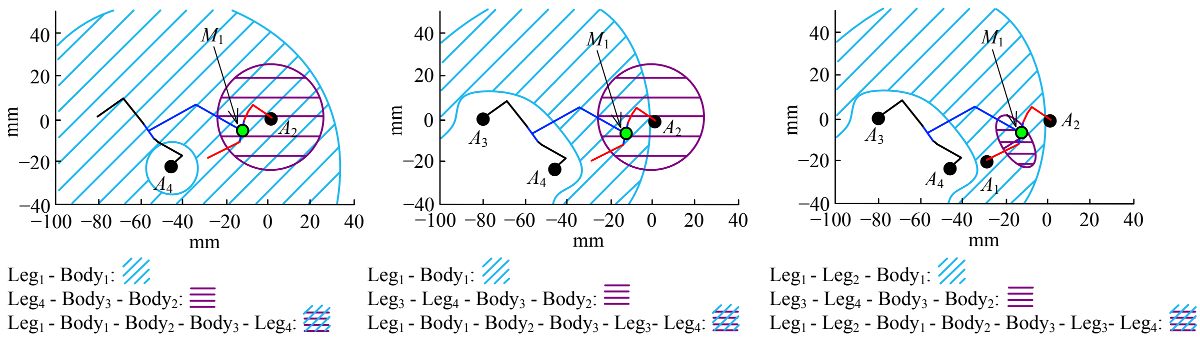
Firstly, the partial workspace is determined. The possible position M_1 can reach is determined by dividing the closed-chain of the kinematic model into two parts based on M_1. The first part consists of Leg$_1$, Leg$_2$ and Body$_1$. The second part contains Leg$_3$, Leg$_4$, Body$_2$ and Body$_3$. If the two forelegs or two hind legs construct a closed-structure, the structure should be considered as a parallel mechanism. For instance, when Leg$_1$, Leg$_2$ and Leg$_4$ construct a closed-structure, it can be divided into Leg$_1$ - Body$_1$ - Leg$_2$ structure and Body$_2$ - Body$_3$ - Leg$_4$ structure, and the Leg$_1$ - Body$_1$ - Leg$_2$ structure should be considered as the parallel mechanism. Then, the reachable workspaces of the two parts are calculated, and the partial workspace is determined as the intersection of the two reachable workspaces. The partial workspace can be categorized into three classes of two, three, and four legs are attached. The result of the calculation is shown in Fig. 7.

The overall workspace can be determined by unionizing the partial workspaces. Therefore the overall workspace cannot be defined if there is no intersection between the current and previous partial workspaces. Since the lengths of legs and body are constant, overall workspaces cannot be defined for some points where feet are attached to the ground.

Strides for each gait, which is defined in Section **4.1**, are determined by the points where the feet are attached to the ground. The 2-0 gait is not considered since the stride of this gait depends on the jumping range and it cannot be decided by kinematic analysis. For a stride becoming feasible, it should be contained in the overall workspace. The maximum strides which are covered by overall workspaces for 4-3-4-3, 4-3-2-3, and 4-2 gaits are 50.9, 68.1, and 97.4 mm per cycle, respectively.

5 Conclusion

This paper proposes a kinematic model and the procedure to generate the gaits of the gecko from experimental data. The closed-chain of the kinematic model is considered as a serial mechanism and constraints are assigned to maintain the position of attached



(a) two legs are attached (b) three legs are attached (c) four legs are attached.

Fig. 7 Calculation of the M_1 workspace of chain.

feet during movement. The resulting locomotion of the kinematic model was successfully validated by comparing it with the experimental data. The kinematic model and the measured gait were used to generate other gaits according to the speeds. The overall workspace of one cycle was defined by summing partial workspaces, and the maximum stride was determined for each gait. The proposed kinematic model can be used in the optimal design, dynamic analysis, and path planning of a biomimetic robot.

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