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ORIGINAL PAPER

Galloping gait analysis of a beetle from the *Scarabaeidae* family

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Abstract

Beetles are six-legged insects that show stability, not only in their walk, but also in other skills, such as that of dragging objects. As a result, their study is of great interest in limb-based mobile robotics. This research studies the dung beetle endemic to Mexico (i.e. genus Canthon) to propose a galloping gait model. First, we analyze video frames of the gait cycle, and then, we estimate the spatial positions of each of the beetle's limbs. Next, we define the equations for the angular position of the inverse kinematic model for one limb. Finally, considering all the limbs as having the same configuration, we perform the simulation of the mathematical model given the obtained spatial position parameters and equations. The results indicate high similarity between the mathematical model and the biological model.

Keywords March cycle · Kinematics · Stability · Robotics

1 Introduction

The Coleoptera is the largest order in the animal kingdom, as it comprises over 500,000 species of insects, including dung beetles. Also known as manure dungs, coprophagous, rollers, or wheelers [1], dung beetles belong within the super family Scarabaeidae, most of them in subfamilies Scarabaeidae, Aphodiinae, and Geotrupinae.

Among the rolling beetles, we can find the genus Canthon, endemic to the mountain range of Jalisco, in western Mexico.

Six-legged insects, such as dung beetles, are characterized by their remarkable stability when walking. Experts have identified a variety of leg combinations that allow coleopterans to move at different speeds. Also, the movement of each leg depends on a support phase – i.e. where the leg supplies support and propulsion to the body – and a transfer phase – in which the leg is lifted off the surface and moved forward to begin another phase of the leg support [2].

Figure 1 depicts the walking combinations identified in insects and the leg numbering convention. Four different fly patterns can be observed. The black bars stand for the support phase, whereas the spaces between bars represent the transfer phase.

The most common ways of walking presented in beetles are the tripod and the leg-by-leg gaits, vastly researched for applications such as mobile robotics (*"*Control Servo-Visual para Robot Hexápodo autónomo implementando un FPGA*"* [3], *"*Control de un robot hexápodo inspirado en el modo de marcha del escarabajo *histeridae* implementando vision artificial*"* [4]).

Conversely, quadrupedal gait (or galloping gait) in beetles of the Scarabaeidae family has not been sufficiently studied.

2 Methodology

2.1 Gait model analysis

We performed the quadrupedal gait analysis using video recordings of a beetle walking. Fig. 2 and Fig. 3 show the frames considered. Notice that, to walk, the beetle lifts its leg from the surface of the soil; then, it lowers the leg back down till it touches the surface again. This is considered a complete cycle for a limb of the beetle. Analyzing all the extremities in each one of the cycles, the galloping gait is formed. In this type of gear, the front legs (L1 and R1) and middle legs (L2 and R2) contribute to its movement, whereas the hind legs (L3 and R3) always remain in the same position. For this reason, we only constructed the graphs of the front and middle legs.

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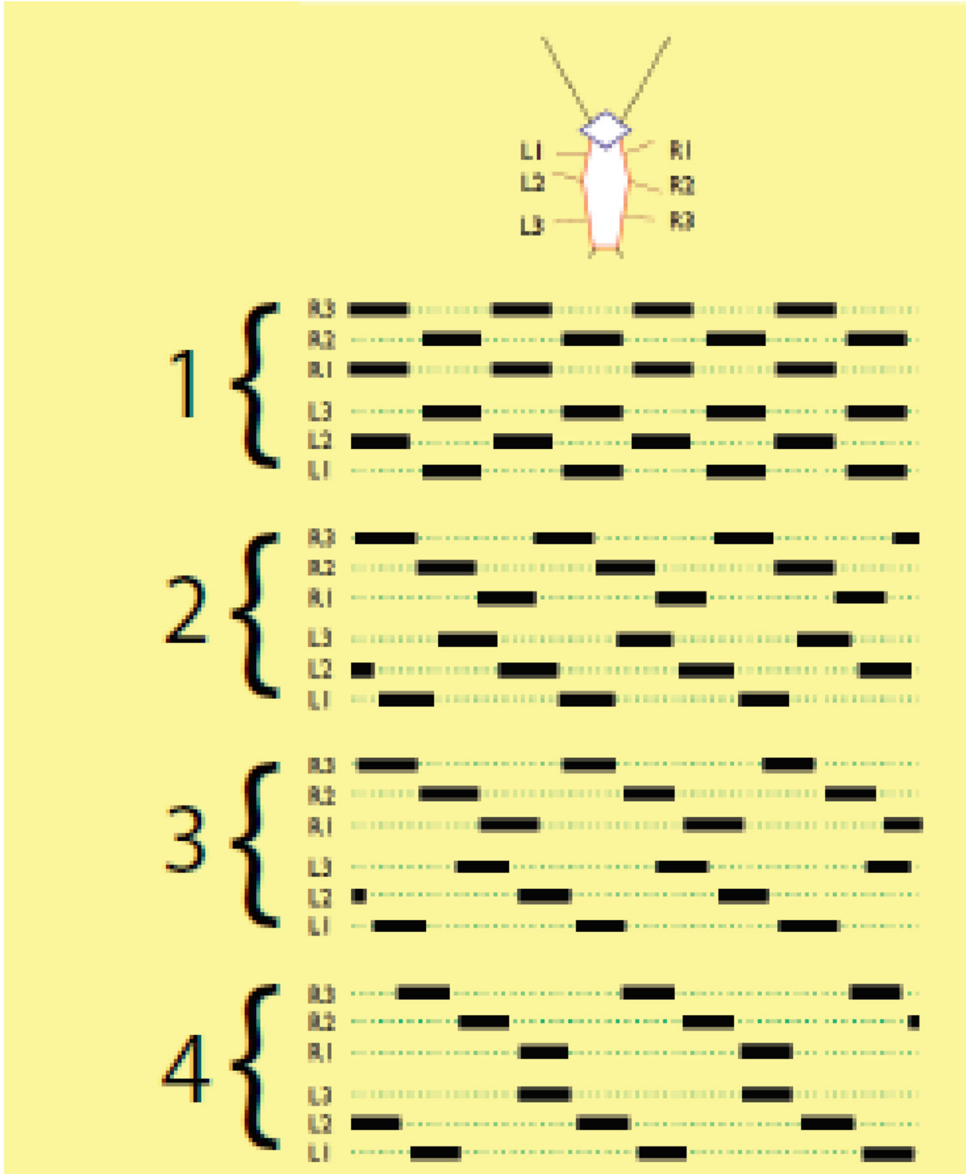

Fig. 1 Walking models for insects. Source: "A phylogenetic analysis of dung beetles (Scarabaeinae: Scarabaeidae): unrolling an evolutionary history"

To simulate this type of gear, the front and middle legs must be considered as having the same distance on the horizontal axis; that is, the length covered by the two types of limbs is the same. On the other hand, the maximum height on the vertical axis is greater in the middle legs than in the front legs, due to the anatomical structure of beetles.

Fig. 2 Analysis of the front tibia. Source: "A new galloping gait in an insect" [5]

Fig. 3 Analysis of the middle tibia. Source: "A new galloping gait in an insect" [5]

Figure 4 shows the trajectory graphs of the beetle front leg (R1), whereas Fig. 5 represents the middle leg (R2). In both Figures, the graph on the left corresponds to the trajectory obtained from the frames. The union of the cycle is observed using line segments due to the discrete shape that exists between each frame. The graphs on the right side of the figures represent the continuous trajectory. To estimate this continuity, we used the cubic spline interpolating function on MATLAB® to ensure smoother movements in the model and thus increase its similarity to the actual beetle limb trajectory.

The interpolated trajectories are recorded in a mathematical model to graphically represent the simulation and thus confirm the results of the analysis of the galloping gait.

Table 1 shows the maximum heights (vertical distance) and the step length (horizontal distance) reached in the galloping gait simulation.

2.2 Kinematic modeling of one beetle limb

To generate the kinematic model of the beetle galloping gait, we analyzed the cycle of only one beetle leg. Then, we considered the same kinematic configuration for the remaining limbs. The one-leg model provided information in terms of leg movement by considering only the limb's geometry and ignoring the forces that generate this movement. In the end, the equations for the general gait model were developed by validating the one-leg model.

Fig. 6 illustrates the coordinate system of one-leg joints, which remains the same in all the limbs.

We applied the Denavit-Hartenberg method [6] to generate the one-leg model as described in eqs. (1), (2), and (3). These equations were the basis of the mathematical model of the beetle gait. They represented the inverse kinematics [7] de-

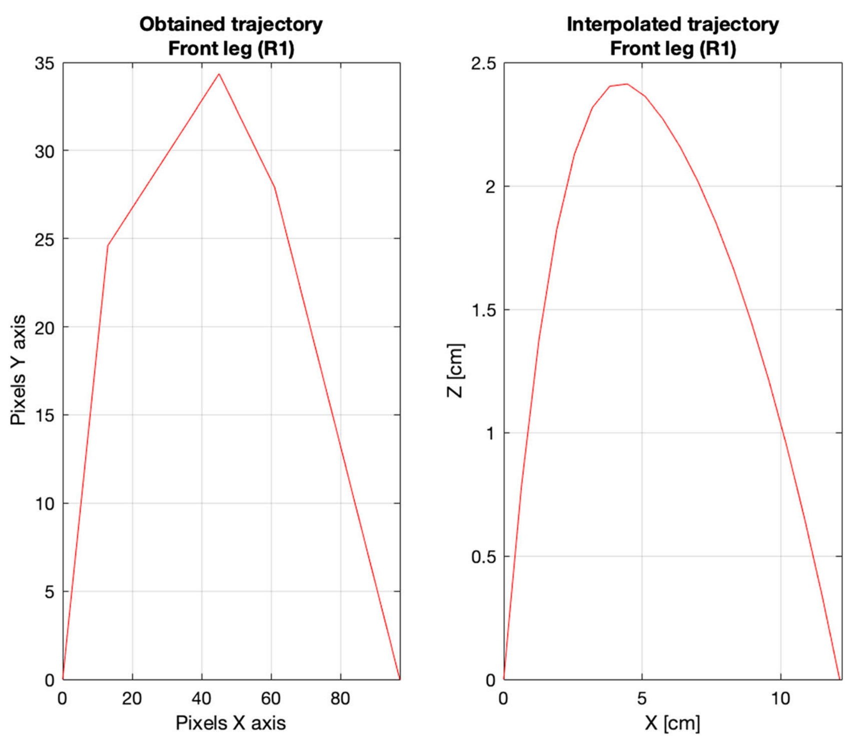

Fig. 4 Trajectory of the beetle front leg

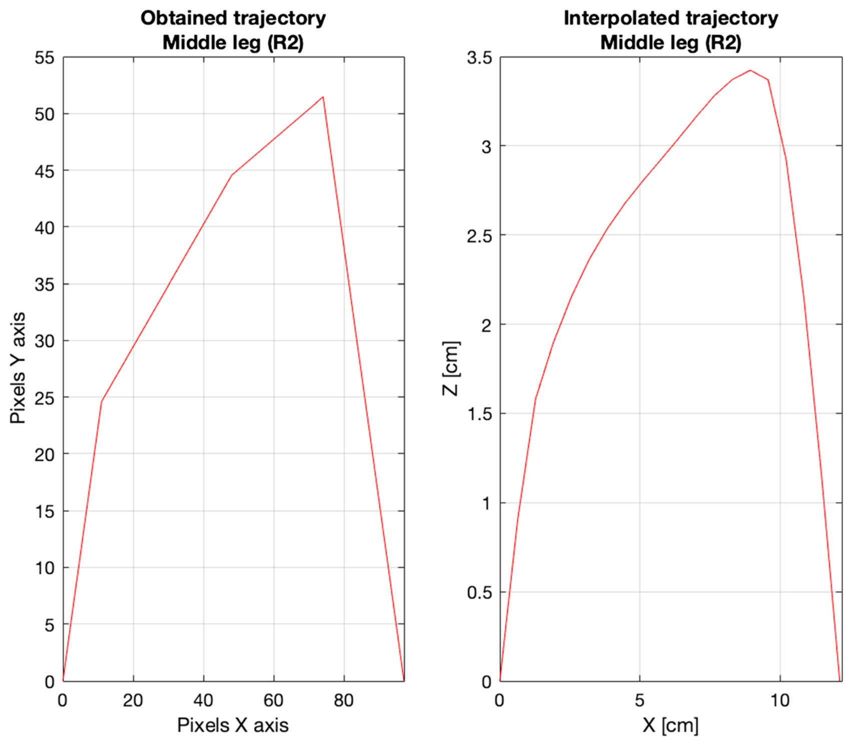

Fig. 5 Trajectory of the beetle middle leg

Table 1 Maximum height and step length reached by the legs of the beetle

Robot legs	Maximum height (Z) [cm]	Step length (X) [cm]
L1 and R1	2.412	12.13
L2 and R2	3.423	12.13

scribing the angular position of each of the three joints that simulated the beetle leg.

$$\theta_1 = \tan^{-1}\left(\frac{Py}{Px}\right) \tag{1}$$

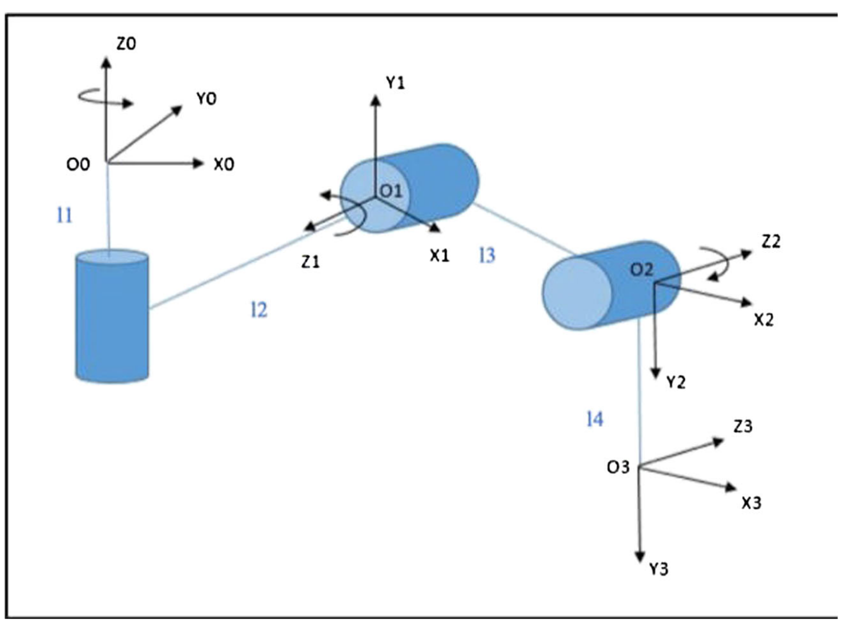

Fig. 6 Establishment of coordinate systems of the joints in the simplified model

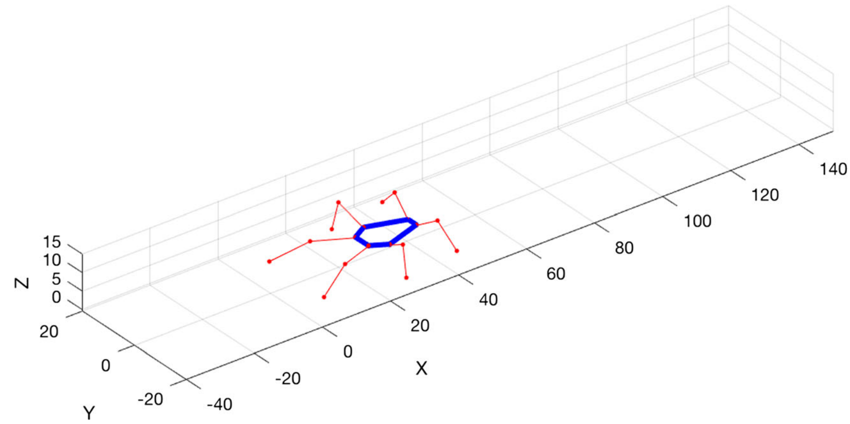

Fig. 7 Galloping gait simulation

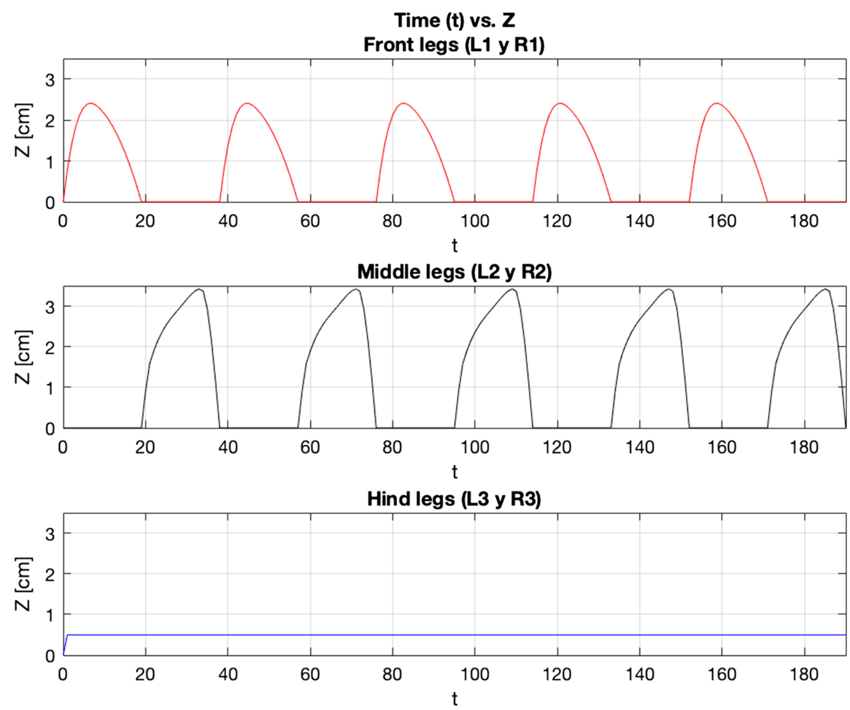

Fig. 8 Graphics obtained from simulating the beetle galloping cycle

$$\theta_2 = \tan^{-1}\left(\frac{Pz - l_1}{L}\right) + \cos^{-1}\left(\frac{-l_3^{\,2} + l_2^{\,2} + R^2}{2 l_2 R}\right) \quad (2)$$

$$\theta_3 = 180 - \cos^{-1}\left(\frac{l_2 \sin(\beta)}{l_3}\right) - (90 - \beta) \quad (3)$$

Table 2 Parameters of the galloping gait simulation

Parameter	Value [cm]	
Maximum height (Z)	Front legs	Middle legs
	2.412	3.423
Step length (X)	12.13	

3 Results

The beetle galloping gait model was simulated on MATLAB®. Fig. 7 depicts the result of the simulation.

To confirm that the model worked properly (i.e. the modeled limbs followed the trajectories as shown in the frames) we plotted the running cycles for each pair of legs as a function of time. In Fig. 8, the upper graph represents limbs L1 and R1, whereas the middle graph represents limbs L2 and R2. Finally, the lower graph corresponds to the non-moving limbs (i.e. L3 and R3).

Table 2 lists the X and Z parameters of the simulation model. These are consistent with those reported in Table 1, previously obtained by analyzing the actual beetle legs.

To determine the similarity between the biological model and the mathematical model, t we calculated the correlation coefficient using the corr2 command on MATLAB®. Since the coefficient value was close to one, namely 0.98, we concluded that the two models were highly similar in terms of the compared signals.

4 Discussion

The parameters from the mathematical model helped us design and construct a hexapod robot that uses its limbs to walk with stability. In addition, the interpolation graphics helped us choose the actuators (motors). It is desirable to get actuators with high resolution on its rotation step; the higher resolution, the greater similarity to the trajectories obtained from the galloping gait simulation.

The frames from which the spatial position parameters are extracted must be parallel (in a lateral view) to the displacement of the biological entity being studied. This ensures high similarity between the mathematical model and the biological model. If this condition is not met, the mathematical model will most likely not correspond to the biological model.

5 Conclusions and perspectives

This work proposes a model of the beetle quadrupedal gait. To develop the model, all the limbs were considered to have the same kinematic configuration, yet we synchronized the displacement parameters in each leg to model the actual gait cycle.

Our simulation demonstrates the relevance of the equations derived from the Denavit-Hartenberg method. Moreover, the correlation analysis confirmed high similarity between the mathematical model and the biological model.

This work also confirms the viability of identifying limb trajectories from a gait analysis to develop limb-based mobile robotic applications. Nevertheless, notice that a robot's performance will not be identical to that of a beetle, particularly in terms of control, strength, and energy efficiency. In other words, the mechanical and electronic tools of a robot cannot be compared with actual limbs, naturally given to insects.

As future work, we suggest performing a gait analysis of the beetle by studying the biological model from multiple views (top, front, and side) and thus generate a 3D model.

Compliance and ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of authors.

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