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Published in:
Artificial Life and Robotics

DOI:
10.1007/s10015-018-0475-5

Publication date:
2018

Document version
Accepted manuscript

Citation for published version (APA):

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Bio-Inspired Design and Movement Generation of Dung Beetle-Like Legs

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\begin{abstract}
African dung beetle \textit{Scarabaeus galenus} can use its front legs for multiple purposes that include walking, manipulating or forming a dung ball, and also transporting it. Its multifunctional legs have not been thoroughly investigated or even used as inspiration for robot leg design. Thus, in this paper, we present the development of real robot legs based on the front leg of the beetle. Each robot leg consists of three main segments which were built using 3D printing. The segments were combined with in total four active joints (i.e., 4 degrees of freedom) in order to mimic the leg movements of the beetle for locomotion as well as object manipulation and transportation. Kinematics analysis of the leg was also performed to identify its workspace. The leg movements of the beetle, during walking as well as manipulating and transporting a dung ball, were observed and reproduced on the robot leg. The results show that the robot leg is able to perform all the movements with trajectories comparable to the beetle leg. To this end, the study contributes not only novel multifunctional robot legs but also the methodologies for both bio-inspired leg design and leg movement generation.
\end{abstract}

\begin{keywords}
Insect legs · Hexapod · Locomotion · Object Manipulation · Motion Analysis
\end{keywords}

1 INTRODUCTION

To date, different types of insect-like walking robots have been developed \cite{1–3}. Examples include the hexapod robots AMOS \cite{1}, HECTOR \cite{2} and BILL-Ant \cite{3} with 3-DOF legs, the hexapod robots LAURON V \cite{4} and ASTERIS \cite{5} with 4-DOF legs, and the hexapod robot WEAVER \cite{6} with 5-DOF legs. While the 3-DOF legs enable the robots to walk on rough terrain \cite{1–3} and to climb over a high obstacle \cite{1}, the kinematic redundancy in the 4- and 5-DOF legs can improve the robot maneuverability on more complex terrains \cite{4–6}. However, all these leg structures have been mainly designed for pure locomotion. If other function, like object manipulation, is required, an additional active gripper or manipulator is installed \cite{4} which, as a consequence, needs extra energy. Furthermore, the added component will increase the robot weight; thereby requiring more torque of the actuators of the legs.

In contrast to all these robots, the African dung beetle \textit{Scarabaeus galenus} can use its legs to walk, manipulate or form a dung ball, and transport it (Fig. 1). Besides walking, the front legs are used mainly for manipulating and forming a dung ball (Fig. 1(a)), the middle legs for pushing the ball, and the hind legs for steering the ball (Fig. 1(b)). From this point of view, biomechanical structures of real beetle legs are a good template for developing multifunctional robotic legs. We have previously developed a dung beetle-like hind leg \cite{7} and its motion control.

In this study, we continue our work \cite{8} by investigating the front leg of the real beetle through \textit{µ}CT and video recordings. Afterwards, we use this biological in-
vestigation to design and develop multifunctional dung beetle-like front legs. Here we also analyze the kinematics of the leg and generate its movements based on the front leg movements of the beetle during locomotion, object manipulation and transportation (Fig. 1). The results show that the movements of the robot leg and the beetle leg are comparable.

Fig. 1. The African dung beetle *Scarabaeus galenus* during (a) locomotion, (b) dung ball manipulation, and (c) dung ball transportation (see Supplementary Video 1).

The main contributions of this paper can be summarized as follows:

- Investigating the front legs of the real beetle through μCT and video recordings.
- Developing real multifunctional dung beetle-like front legs based on the biological investigation.
- Analyzing the leg kinematics.
- Generating the leg movements with comparable trajectories to the beetle leg’s movements during walking as well as manipulating and transporting a dung ball.

This paper is organized as follows. In Section 2, we introduce the methodology of the bio-inspired leg design. In Section 3, we present kinematic analysis of the leg. In Section 4, we present the methodology of the dung beetle-like leg movement generation and experimental results on leg trajectories. This paper finishes in Section 5 with discussion and conclusions. Here, results are provided alongside the introduced components from which they mainly derive because this provides a better understanding of their functionalities.

2 BIO-INSPIRED DESIGN METHODOLOGY

To achieve a multifunctional robotic leg that can perform locomotion as well as object manipulation and transportation we investigated the front leg of the African dung beetle *Scarabaeus galenus* through video recordings and μCT scans. For video recordings, we filmed the dung beetle while walking and manipulating and transporting a dung ball (see Fig. 1) and then analyzed the front leg movements frame by frame. This was done to observe the range of leg movements.

In order to obtain kinematic details (including joint orientations and axes as well as the number of degrees of freedom (DOF)) of the front leg, we scanned the leg through a desktop μCT scanner (Skyscan 1172). The scanner captures x-ray images over a 360° rotation of the beetle. Based on these images, we reconstructed a 3D dataset that consists of a stack of virtual cross-section images through the entire specimen. Then we interactively segmented the parts of the leg from the dataset by assigning different labels to individual pixels within the stack of cross-sectional images. The segmented structures can then be visualized independently from the rest of μCT dataset and be exported as polygonal surfaces. Fig. 2 summarizes the step by step of the bio-inspired design process.

Through the design process, we can identify three main segments of the leg, which include coxa, femur, and tibia with tarsus (Fig. 3(a)). There are three main active joints: TC-joint (connecting thorax and coxa), CT-joint (connecting coxa and trochanter+femur), and FT-joint (connecting trochanter+femur and tibia). Trochanter and femur segments are connected by a joint which allows very small movements; therefore, we simplified it as a fused component. The TC-joint is the most complex one which acts as a biaxial joint allowing for motions within two planes. Thus, we constructed this joint with two actuators that rotate around the y- and z-axes. The CT- and FT-joints are the simple ones which act as monoaxial joints allowing for motions within one plane each (Fig. 3(b)). Thus, we constructed each joint with one actuator that rotates around the x-

Fig. 2. (a) *Scarabaeus galenus* beetle (b) μCT scan of the beetle, (c) exoskeleton of the beetle, (d) exoskeleton after segmentation and reconstruction, (e) a dung beetle-like robotic leg.

1 www.manoonpong.com/DungBeetle/SGBeetle.wmv
axis. In total four actuators are used for the leg. Due to the actuator constraints, each segment of the leg was scaled 10 times from the original size. The size of each segment is approx. 26 mm for coxa, approx. 60 mm for femur, and approx. 100 mm for tibia with tarsus. The overall leg length including connections between segments is approx. 370 mm.

For the TC-joint, we used two HS-645MG servo motors where each of them can provide a torque of 1 N.m and a speed of 0.0033 s/deg. For the CT- and FT-joints, we used two BMS-380MAX servomotors where each of them can provide a torque of 0.5 N.m and a speed of 0.0023 s/deg. All the servo motors are driven by a controller through the Multi-Servo IO-Board (Mboard). The Mboard is interfaced with a personal computer (PC) via RS232 serial connection at 57.6 kbits per second.

Taken together, the dung beetle-like front leg has the following characteristics:

1. The first motor $q_1$ of the TC-joint, rotating around the $z$-axis, moves the leg forward and backward.
2. The second motor $q_2$ of the TC-joint, rotating around the $y$-axis, can orient the leg downward mainly for object manipulation.
3. The third and fourth motors $q_3$ and $q_4$ for the CT- and FT-joints, rotating around the $x$-axis, are responsible for moving the leg toward or away from the body.
4. The length of the coxa segment is about 2 times and 3 times smaller than femur and tibia with tarsus segments, respectively.
5. The motors of the TC-joint require a high torque in order to move the entire leg, while the other two motors require a smaller torque since they move only the remaining leg excluding the coxa part.
6. All segments and connectors were 3D printed using pure PolyLactic Acid (PLA) thermoplastic, except the tibia with tarsus where we used a combination of PLA and a soft material (i.e., rubber) in order to obtain proper friction between the leg and the surface during locomotion and object manipulation.

3 KINEMATIC ANALYSIS

Here we present the kinematics of the 4-DOF dung beetle-like front leg (Fig. 3) in two parts: Forward kinematics using the Denavit-Hartenberg (DH) method and inverse kinematics using a differential kinematic method.

3.1 Forward Kinematics

The kinematic diagram of the leg with the coordinate frame assignment is shown in Fig. 4. The Denavit-Hartenberg (DH) parameters and the rotational ranges of all motors are listed in Table 1 and Table 2, respectively. $(x_r, y_r, z_r)$ represents the reference frame, $(x_b, y_b, z_b)$ the body frame, and $(x_1, y_1, z_1)$ to $(x_4, y_4, z_4)$ the local coordinate frames at the four motors respectively. $(x_c, y_c, z_c)$ shows the local coordinate frame at the tip of the leg. The transformation matrix of the leg is de-

![Fig. 3. (a) Dung beetle front leg, (b) the 4-DOF dung beetle-like front leg.](image)

![Fig. 4. Kinematic diagram of the leg configuration. Motor 1 ($q_1$) and Motor 2 ($q_2$) belong to the TC-joint. Motors 3 ($q_3$) and Motor 4 ($q_4$) belong to the CT- and FT-joints, respectively.](image)

<table>
<thead>
<tr>
<th>Link</th>
<th>$\theta_i$</th>
<th>$d_i$</th>
<th>$a_i$</th>
<th>$\alpha_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor 1</td>
<td>$q_1$</td>
<td>$L_1$</td>
<td>$-\pi/2$</td>
<td>0</td>
</tr>
<tr>
<td>Motor 2</td>
<td>$q_2$</td>
<td>$L_2$</td>
<td>$-\pi/2$</td>
<td>0</td>
</tr>
<tr>
<td>Motor 3</td>
<td>$q_3$</td>
<td>0</td>
<td>0</td>
<td>$L_3$</td>
</tr>
<tr>
<td>Motor 4</td>
<td>$q_4$</td>
<td>0</td>
<td>0</td>
<td>$L_4$</td>
</tr>
</tbody>
</table>
scribed as:

\[
T_i^{t+1} = \text{Rot}_{z, \theta_i} \cdot \text{Trans}_{z, d_i} \cdot \text{Trans}_{s, \alpha_i} \cdot \text{Rot}_{s, \alpha_i}
\]

\[
= \begin{bmatrix}
  c_\theta \cdot s_\alpha & -s_\theta \cdot s_\alpha & s_\theta \cdot c_{\alpha} \\
  s_\theta \cdot c_\alpha & c_\theta \cdot c_\alpha & -s_\alpha \\
  0 & s_\alpha & c_\alpha
\end{bmatrix}
\]

where \(c_x\) and \(s_x\) denote \(\cos(x)\) and \(\sin(x)\) respectively.

\[
T_c = T_2 \cdot T_3 \cdot T_4 = \begin{bmatrix}
  n_x & o_x & p_x \\
  n_y & o_y & p_y \\
  n_z & o_z & p_z
\end{bmatrix}
\]

with \(c = [p_x, p_y, p_z]^T\). Therefore, the position of the foot with respect to the global coordinate frame is given by:

\[
p_x = L_3(S_1 S_3) - L_2(S_1) + L_4 C_4(S_1 S_3 + C_1 C_2 C_3)
\]

\[
+ L_4 S_4(C_1 S_3 - C_1 C_2 S_3) + L_4(C_1 C_2 C_3),
\]

\[
p_y = L_2 C_1 - L_3 C_3 S_3 - L_4 C_4(C_1 S_3 - C_2 C_3 S_3)
\]

\[
- L_4 S_4(C_1 C_3 + C_2 S_3 S_1) + L_4(C_2 C_3),
\]

\[
p_z = L_1 - L_3 C_3 S_2 - L_4(C_3 C_4 S_2) + L_4(S_2 S_3 S_4),
\]

where \((n_x, n_y, n_z)^T\), \((o_x, o_y, o_z)^T\), and \((p_x, p_y, p_z)^T\) are the orientation vectors of the foot tip.

### 3.2 Inverse Kinematics

We employed common closed-loop methods that are used for redundant robots [9]. The differential kinematics equation represents a linear mapping between joint angular velocities \([\dot{\theta}_1, \dot{\theta}_2, \dot{\theta}_3, \dot{\theta}_4]^T\) and foot tip velocities \([\dot{p}_x, \dot{p}_y, \dot{p}_z]^T\). Therefore, the differential kinematics equation can be described as:

\[
\dot{x}_c = v_c = J(q) \dot{q},
\]

where \(v_c\) is here the \(r \times 1\) vector \((r=3)\) of foot tip velocity for the specific task and \(J\) is the corresponding \((r \times n)\) \((r=3, n=4)\) Jacobian matrix, and \(\dot{q}\) is the \(n \times 1\) vector of joint velocities\((n=4)\). Let

\[
e = x_d - x_c
\]

be the expression of error, where \(x_d\) is the desired position and \(x_c\) is the actual position of the leg foot tip. The time derivative of Equation (7) is given by:

\[
\dot{e} = \dot{x}_d - \dot{x}_c.
\]

According to differential kinematics, Equation (6) can be written as:

\[
\dot{e} = \dot{x}_d - J(q) \dot{q}.
\]

Notice that Equation (9) leads to an inverse kinematics algorithm, it is worth relating the computed joint velocity vector \(\dot{q}\) to the error \(e\) so that Equation (9) gives a differential equation describing error evolution over time. Nonetheless, it is necessary to choose a relationship between \(\dot{q}\) and \(e\) that ensures convergence of the error to zero. Having formulated inverse kinematics in algorithmic terms implies that the joint variables \(q\) corresponding to a given leg pose \(x_d\) are accurately computed when the error \(x_d - k(q)\) as a function of \(e\) permits finding inverse kinematics algorithms with different features, where \(k\) indicates the forward kinematics. On the assumption that the \(J(q)\) is the square matrix and non-singular, the choice

\[
\dot{q} = J^{-1}(\dot{x}_d + Ke)
\]

leads to the equivalent linear system

\[
\dot{e} + Ke = 0.
\]

Solution (11) can be generalized for the case of the redundant leg, which gives

\[
\dot{q} = J^*(\dot{x}_d + Ke),
\]

where \(J^* = JT(JJT + \lambda^2 I)^{-1}\) and \(K\) is a positive definite, usually diagonal matrix, \(\lambda\) is the Lagrange multiplier and \(I\) is the identity matrix. In developed algorithm, desired target \((x_d)\) is constant, therefore, \((\dot{x}_d)\) is zero. So the final equation is

\[
\dot{q} = J^* \cdot (Ke).
\]

The block diagram corresponding to the inverse kinematics algorithm given by Equation 13 is illustrated in Fig. 5.

To evaluate the performance of our inverse kinematic control, we let the leg tip follow a cubic polynomial trajectory. To do so, we set the leg at the initial orientation \(q = [0, \pi/4, -\pi/4, \pi/3]^T\) rad where the corresponding initial position is \([15.2, 10.00, -13.2]^T\) cm. The end position \([7.6, 2.7, -7.6]^T\) cm is given as an input to the control. Intermediate positions are assigned with respect to the polynomial trajectory. Fig. 6 shows the profiles of the joint positions \([q_1, q_2, q_3, q_4]^T\) and velocities \([\dot{q}_1, \dot{q}_2, \dot{q}_3, \dot{q}_4]^T\) that follow the polynomial trajectory. Note that the initial \(v_0\) and final \(v_f\) velocities are considered to be zero.

<table>
<thead>
<tr>
<th>Joint</th>
<th>(\theta_{\text{min}})</th>
<th>(\theta_{\text{max}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor 1</td>
<td>(\pi/4)</td>
<td>(\pi/4)</td>
</tr>
<tr>
<td>Motor 2</td>
<td>(\pi/4)</td>
<td>(\pi/4)</td>
</tr>
<tr>
<td>Motor 3</td>
<td>(\pi/4)</td>
<td>(\pi/4)</td>
</tr>
<tr>
<td>Motor 4</td>
<td>(\pi/4)</td>
<td>(\pi/4)</td>
</tr>
</tbody>
</table>
4 LEG MOVEMENT GENERATION METHODOLOGY

Here, we describe a methodology for generating dung beetle-like front leg movements (during normal walking and manipulating and transporting a dung ball) and validating them. The methodology consists of four steps (Fig. 8):

1) Tracking insect foot tip positions (i.e., dung beetle’s foot tip),
2) Simulating a bio-inspired leg (i.e., simulated dung beetle-like front leg) with inverse kinematic implementation (here, see Fig. 5),
3) Transferring to a real robot (i.e., real dung beetle-like front leg),
4) Validating robot foot tip positions (i.e., the beetle-like leg’s foot tip).

In principle, this framework can also be applied to other bio-inspired robotic systems.

3.3 Workspace Comparison between the 4-DOF dung beetle-like leg and a standard 3-DOF leg

Fig. 7(a) shows the workspace of the dung beetle-like front leg. Due to the second degree of freedom ($q_2$) of the TC-joint, the positions in the reachable workspace span an extensive volume. In contrast, if the degree of freedom is fixed where the leg becomes a 3-DOF robot leg, the workspace is reduced (Fig. 7(b)). This demonstrates that our bio-inspired leg design provides an extended workspace which is useful for complex actions, like object manipulation and transportation of the dung ball.

Fig. 7. Aditya: The workspaces of (a) the 4-DOF dung beetle-like leg and (b) the standard 3-DOF robot leg.

Step 1: Tracking insect foot tip positions

Real dung beetles were recorded during walking, manipulating or forming a dung ball, and transporting it. We used a video tracking tool (called Tracker 2) to analyze the foot tip positions/trajectories of a front leg of the beetle in the two-dimensional plane (x-y) by frame. Fig. 9 exemplifies the assignment of the coordinate frame for tracking the foot tip positions.

Here we used the position of the center of mass of the beetle ($M_i(x_{m_i}, y_{m_i})$) as a frame of reference to calculate the relative foot tip position ($R_i(x_{r_i}, y_{r_i})$) of the beetle from the tracked foot tip position ($F_i(x_{i}, y_{i})$). This calculation is governed by the following equation:

$$R_i = F_i - M_i$$  \hspace{1cm} (14)

Fig. 8. Methodology for generating insect-like leg movements. $x_i, y_i$ and $x_r, y_r$ are the foot tip positions of an insect and a real robot in the two-dimensional plane (x-y), respectively. $q_1, q_2, ... , q_n$ are the joint positions.
Fig. 9. Example of the assignment of the coordinate frame for tracking the foot tip positions. This snapshot shows the beetle transporting a dung ball.

Fig. 12 shows the snapshots of tracking the foot tip positions for three actions.

**Step 2: Simulating a bio-inspired leg with inverse kinematic implementation.**

We used the physical simulator V-REP \(^3\) to simulate the 4-DOF dung beetle-like front leg with its inverse kinematic implementation (see Fig. 5). To obtain the precise dimension and kinematic structure of the leg, the CAD model of the leg was imported into the simulation. We used the simulated leg to perform preliminary testing and acquire joint angle positions. The joint angle positions were used to drive the real robot leg (Step 3). The relative foot tip positions \((x_{ri}, y_{ri})\) obtained from Step 1 were given as inputs to the simulation. Fig. 10(a) shows the imported CAD model of the leg in the simulation. For computational efficiency and stability, the CAD model was simplified into a dynamically active model (Fig. 10(b)). Furthermore, parts of the dynamically active model were approximated into groups of cylinders and cuboids. A collision detection mode was done by using an integrated ODE during simulations. Fig. 13 shows the snapshots of the movements of the simulated leg and its changing joint angle positions with respect to the dung beetle actions (i.e., walking, manipulating a dung ball, and transporting it).

**Step 3: Transferring to a real robot**

As shown in Fig. 10(c), the robot legs were built by using the design methodology described in Section 2. The legs were attached to a supporter for generating dung beetle-like movements in the 2D plane. The joint angle signals, obtained from the simulation described in Step 2, were translated into motor commands to drive the real robot leg. Fig. 13 shows the snapshots of the robot prototype performing all the three dung beetle-like movements, each of which demonstrates a complete cycle.

**Step 4: Validating robot foot tip positions**

Experiments were conducted, and the foot tip trajectories of the robot prototype were recorded. The video tracking tool (Tracker) was used to analyze foot tip movements. The foot tip movements during locomotion, dung ball manipulation, and dung ball transpor-

\(^{3}\) http://www.coppeliarobotics.com/
Fig. 12. Snapshots of tracking the foot tip positions of the dung beetles during (a) walking, (b) manipulating a dung ball, and (c) transporting it. We encourage the reader to see the videos of this experiment [10].

Fig. 13. Snapshots of the leg movements and the foot tip positions of the real robot following the three actions of dung beetles (cf. Fig. 10): (a) walking, (b) manipulating a dung ball, and (c) transporting it. We encourage the reader to see the videos of this experiment [10].
tation of the beetle leg were validated (Fig. 14(a)) with the robot leg movements (Fig. 14(b)). It can be seen that the robot leg is able to perform all the movements with comparable trajectories to the beetle leg.

![Diagram](image-url)

**Fig. 14.** Validation of the generated robot leg trajectories with the dung beetle leg trajectories for (a) walking, (b) manipulating a dung ball, and (c) transporting it.

5 CONCLUSION

We presented a way of designing bio-inspired legs in a systemic way and outlined the design procedure, which is based on \( \mu \)CT scans of a real dung beetle. We used the data to construct the real dung beetle robot leg with 4 DOFs that allows for dung beetle-like leg movements for locomotion as well as dung ball manipulation and transportation. We performed the kinematic analysis where closed-loop methods were employed for solving the inverse kinematic problem of the leg. To check the efficacy of the implemented inverse differential kinematic control, closed loop trajectories are generated in the joint and Cartesian spaces. Our experiments show that the use of additional DOF extends the workspace (see Fig. 7), which makes our design applicable for performing multiple tasks in addition to a standard 3-DOF leg. We also presented a way of generating dung beetle-like leg movements in the real robot leg. The leg movements were based on 2D data extracting from the video recordings of the real dung beetles.

For future work, we will use 3D data for generating more realistic movements. Neural control mechanisms [11] with sensory feedback and muscle models [12] for adaptive leg movements and joint compliance will be also investigated. We will also develop the robot body and the remaining middle and hind legs to complete the dung beetle robot as a bio-inspired multifunctional robotic system.

Acknowledgements

This work was supported by Center for BioRobotics (CBR) at University of Southern Denmark (SDU, Denmark) and the Human Frontier Science Program under grant agreement no. RGP0002/2017.

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