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Advantages of using a biologically plausible embodied kinematic model for enhancement of speed and multifunctionality of a walking robot

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Abstract: A typical approach when designing a bio-inspired robot is to simplify an animal model and to enhance the functionality of interest. For hexapod robots, this often leads to models with an unknown performance; thereby influencing their functionality and requiring supplementary mechanics to become multifunctional. A preferable solution is to employ the embodied multifunctional capabilities of the animal as inspiration for robot design. For this reason, we present a method for translating the kinematic chain of a dung beetle, from which an accurate model and a simplified one were created and simulated. A comparison between the two modeling approaches shows a similar performance in regards to walking stability and accuracy, but differences when it comes to speed and multifunctionality. Here the accurate model outperforms the simplified model, by both walking faster and being capable of performing additional locomotory tasks. In conclusion, the accurate model of a dung beetle-inspired robot is advantageous in regards to multifunctional abilities including walking as well as standing on and rolling a ball, like a dung beetle.

Keywords: Bio-inspired robotics, Embodied AI, Multipurpose kinematics, Adaptive locomotion, Walknet, Dung beetle

1. INTRODUCTION

Bio-inspired robotics is a growing field, aimed at using natural features of animals as an inspiration for robotic design [1-4]. Animal models are often complex and adapted to a specific set of tasks according to their habits. This makes them multifunctional. Most designers, however, simplify the model and enhance the functionality of interest, resulting in kinematics and dimensions different from those of the animal being used as a model [5].

Examples of projects concerning walking animals with these approximations are the HECTOR robot, based on the studies of stick insects [4], and the AMOS robot inspired by a cockroach [6]. Most striking for these projects is the oversimplified legs, which are all identical with simplified kinematics. This particular approximation is often seen and it is also the reason why many of today's hexapod leg models have kinematics similar to the one shown in figure 1. Bio-inspired models with these leg approximations are usually designed entirely for locomotion purposes, while ignoring the multifunctional aspects of the animal locomotion. Thus, in order to perform additional functions, supplementary mechanics and actuators need to be installed [7]. The efficacy of the simplifications is often unknown, meaning that they may in fact weaken – instead of enhancing – the functionality of interest.

A preferable solution is to use the embodiment of the animal, which is capable of being multifunctional and

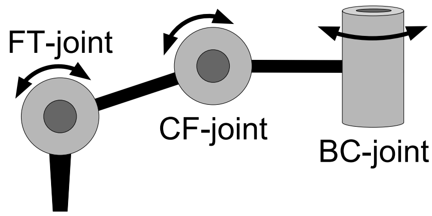

Fig. 1 Leg kinematics commonly used as approximation to an animal leg. Each join controls only one degree of freedom for the endpoint. The BC-joint furthest to the right is attached to the body of the robot.

presumably optimized by evolution. One animal in possession of multifunctional legs is a dung beetle, an insect that can both walk and manipulate a spherical object. The beetle uses its skills to transport balls of dung away from competitors onto soft ground where it can bury the dung [8]. From the robotic point of view, the beetle shows fascinating abilities due to the fact that it uses its legs for both locomotion and manipulation related tasks [9].

To investigate our modelling assumptions, we developed a kinematic model of a dung beetle (*Geotrupes stercorarius*) with a minimal use of approximations and compared it to a version with simplified leg kinematics (see Fig. 1), to see whether any significant differences exist. Both models are simulated, and are controlled by WALKNET, a controller based on the principles of behaviour-based AI [10]. WALKNET was introduced in 1998 by Cruse and his team [11], who in essence reverse-

† Mathias Thor is the presenter of this paper.

engineered the locomotion behavior of a stick insect. The controller has been used to control many different simplified robots [12].

The objectives of this paper are thus to describe the research needed in order to model a dung beetle accurately (section 2.1) and to – briefly – describe the WALKNET controller and the reason why this controller is a good choice when controlling bio-inspired models (section 2.2). Finally, we will compare the two models in order to determine the strengths and weaknesses of the two modeling approaches (section 2.3, 3, and 4).

2. METHODS

2.1. Biological Investigation

When developing a biologically accurate model of a dung beetle, it is first of all necessary to know its exact kinematics and anatomy. These are analysed and measured with a measuring microscope (Mitutoyo) capable of capturing 3D Cartesian position and a micro-scale with a precision down to 1 microgram. The dung beetle species examined is the *Geotrupes stercorarius*, which is shown in figure 2 annotated with the body parts and joints to be measured. Note here that the pretarsus, located at the end of the tarsus, is merged together with the rest of the tarsus and that the trochanter, located between the coxa and femur, is merged with the coxa, as suggested by Canio et al. [13]. Figure 2 shows that the beetle has a bilateral symmetry, meaning that the two hind legs, the two middle legs and the two front legs are mirrored. This makes it possible to generalize the measurements from one side of the beetle to the other by relating each leg to the symmetry line.

The weights and dimensions of the different body parts are found by detaching and measuring each individual part with the micro-scale and the microscope. Here the measuring microscope is used for establishing three 3D vectors on each part, from which the height, width and length are easily derived.

The measurement microscope is likewise used to derive some of the dung beetle kinematics, including joint configuration and rotational range of motion for each joint. It is, however, possible to determine the rotational range of motion for the CF- and FT-joints by visual inspection. This is due to the fact that these joints are able to retract the legs completely to compactise the legs to the body and reduce damages during predator attacks. The rotational range of motion for the BC-joint is harder to measure, as neither their minimum nor maximum positions can be easily determined. This rules out the use of visual inspection, as it will result in too large approximations. Instead two 3D vectors, one representing the coxa and another the femur, are measured for each BC-joint's maximum and minimum positions. A plane can then be created for each configuration utilizing the vector pairs, and the angle between the planes represents the rotational range of motion for the BC-joint. Finally, the positions of the coxae with respect to the body are measured, in order to attach the legs correctly on the body. This is also done

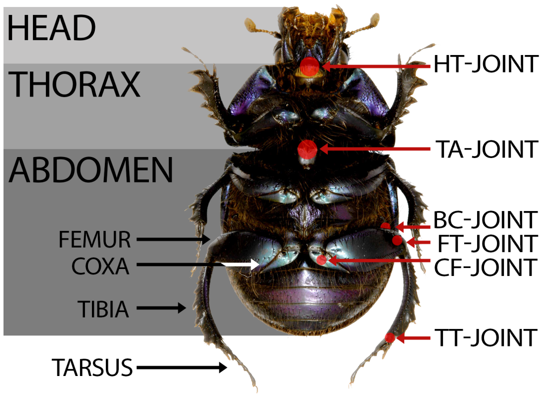

Fig. 2 Body part and joints of the *Geotrupes stercorarius*. Leg parts are indicated with black arrows, where the coxa placement is shown with a white arrow indicating that it is located behind the femur. Joints are indicated with red dots and red arrows. Note that the coxa and trochanter are merged to the single segment. The dung beetle image is modified from [14].

with the help of vector calculations and the measurement microscope, since visual inspection would also produce too large approximations in this case.

2.2. Behavior Control

The WALKNET controller to be used in the dung beetle-inspired model is mainly chosen due to its behaviour-based approach [10]. The idea behind the approach is to use simple rules divided into different layers together with signals from the robot's sensors. From these layers of rules – all grounded in their physical interactions – complex behaviors are expected to emerge [10], where the complex behavior in this case is the locomotion of the dung beetle robot. An advantage of WALKNET is thus its decentralized architecture, which follows from the fact that each leg has its own controller/module working on sensory inputs. This design is in accordance with the real dung beetles, as their small brains are presumably unable to handle centralized locomotion control which requires simultaneous control of up to at least 18 joints (*E. Baird, personal communication*). In addition WALKNET does not use a predefined walking gait. Instead, the gait emerges from the fact that each leg-controller has the capacity to decide the state it should be in, by following six basic coordination rules [11].

Since WALKNET is a locomotion controller, it is necessary to extend it to introduce multifunctionality in the form of a dung-ball rolling behavior. This extension can be achieved by adding an extra behavioral layer to the underlying behavioural control architecture [15].

2.3. Simulation and Experimental Setup

Based on the biological investigation described above, we simulated two versions of a dung beetle-inspired robotic model (i.e., accurate and simplified versions) using the Modular Robot Control environment embedded in the LPZRobots simulation toolkit [16]. The accurate version uses a minimum of approximations and is com-

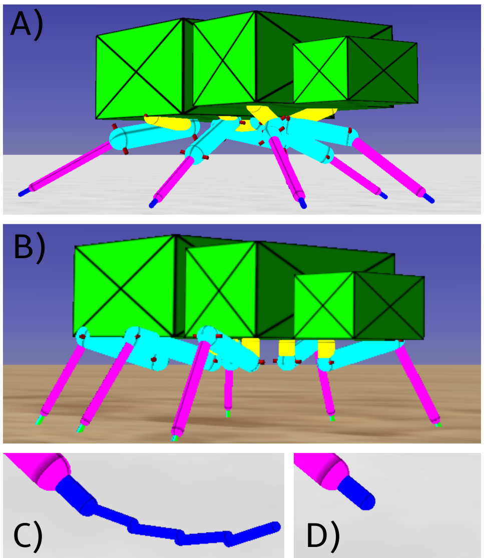

Fig. 3 A) The accurate version. B) The simplified version. C) Leg with all five tarsus segments. D) Leg with only the first tarsus segment (basitarsus).

pletely based on the data derived from the biological investigation, see Fig. 3A. The simplified version is, on the other hand, allowed approximations as it focuses on the locomotion aspect while simplifying other functionalities, see Fig. 3B.

Each version has a total of 50 joints: three on each leg, five on each tarsus and two on the main body. All 50 joints are necessary for the model; besides working as normal joints, they link the different body parts, and thereby the primitives, together. The fact that each tarsus, as shown in Fig. 3C, consists of five joints and five primitives requires a lot of processing power while running the simulation. Four of the tarsus segments are thus made optional, and not used during the experiments, in order to avoid heavy CPU load. Furthermore, since the main purpose of the tarsus is to generate adhesive force in manipulation related tasks [17], the missing tarsus segments can be compensated for by instantiating the remaining segment, see Fig. 3D, with additional adhesive force.

In order to compare the two versions, their locomotion, stability, and ability to transport a ball are tested. Each experiment was performed for 120 seconds. At the beginning of the test the simulated robot is in a transient state where it tries to find a proper gait, causing swerving and unpredictable movements. The transient state is not included in the evaluation of robot performance.

During the test, measurements of walking stability, accuracy and speed are conducted. The stability is defined as the deviation in height during the walk and the accuracy as the amount the model deviates from a straight path. The walking speed is defined as the distance each model is able to cover during the walking test.

To determine whether the the two versions are multifunctional or not, their ability to get into configurations that allow them to perform two common dung beetle tasks is tested. The first configuration is the one where

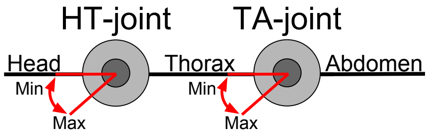

Fig. 4 Kinematics derived form the body of the dung beetle specimen, both the HT- and TA-joints are revolute joints. The dimensions of the body parts are shown in table 4.

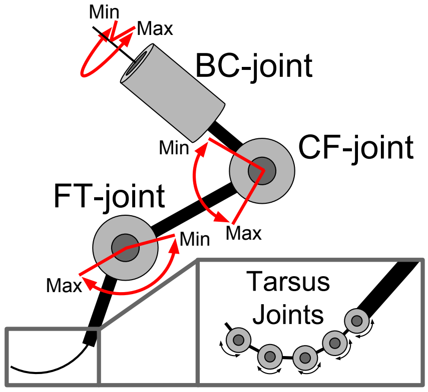

Fig. 5 Kinematics derived from the leg of the dung beetle specimen. The BC-joint is a pivot joint, while the CF- and FT-joints are revolute joints. The dimensions of the leg parts are shown in tables 1-3.

the dung beetle stands on top of a dung ball and the second is the one that allows the dung beetle to roll a dung ball (see Figs. 6A and 6C).

3. RESULTS

3.1. The Dung Beetle-Inspired Robotic Model

The results from the body and leg part measurements are shown in tables 1-4. Note that the tarsus was not weighted due to crumbling during the detachment and its minimal use in the model.

The results shows a variation in the dimensions of the legs for the accurate version, where the hind legs are the longest, then the middle legs and finally the front legs as the shortest. The legs are therefore not identical (see Fig. 3A), which is different from the identical legs of the simplified version (see Fig. 3B).

Figure 4 shows the derived kinematics of the body where two joints are present. It can be seen from visual inspection that these joints are able to bend the beetle downwards, each by approximately 45° resulting in a 90° bend. Figure 5 shows the derived kinematics of a dung beetle leg, where a total of eight joints are shown. Each leg was found to have the same joint configuration, but with different rotational ranges of motion at the BC-joints. The examination showed that the CF- and FT-joints, for all of the legs, are able to rotate approximately 90° and 170° from a fully retracted position. The hind-leg BC-joint was found to have a rotational range of approximately 160°, the middle-leg BC-joint approximately 116°, and the front-leg BC-joint approximately 95°, all found using the measuring microscope.

The placements of the coxae and thus the orientation of the BC-joints was also found to be different form the simple version. This can seen by comparing the orientation of BC-joint in figure 1 with the one in figure 5. The hind-leg BC-joint was found to be oriented 66° inwards towards the center of the beetle from a vertical position and 66° forwards towards the head of the beetle. For the middle-leg BC-joint this was found to be 53° inwards and 58° forwards, and for the front-leg BC-joint 58° inwards and 67° forwards.

3.2. Comparison between the Accurate and Simplified Versions

The resulting means and standard deviations for the locomotion ability tests can be seen in tables 5 and 6.

The results from the walking stability test shows a small height deviation in both versions, which are not significantly different (P = 0.79), indicating that the versions are equally stable.

The results from the accuracy test shows that neither the accurate version nor the simplified version is able to walk in a perfectly straight line. The mean deviations – from the straight path – for both versions are not significantly different (P = 0.23), while the standard deviations are found to be different (P = 3.04e-14). This indicates that the two versions walk equally accurately and that the simplified version is more consistent when compared to the accurate version.

The result from the walking speed test shows that the two versions have different performance, both with regards to the mean (P = 4.18e-07) and standard deviation (P = 0). The simplified version is again more consistent, but this time the accurate version has a much better performance when comparing the mean distance walked. The accurate version is on average able to walk 13.79 cm further in the walking test compared to the simplified one. The video that shows the walking behavior of the accurate version comparing with a dung beetle can be seen at www.manoonpong.com/DungBeetle/svideo.wmv.

Finally, the results from the multifunctionality test shows that the accurate version is able to stand on and roll a dung ball, as shown in figure 6. The simplified version is on the other hand not considered multifunctional, since it is not possible to put it in a configuration that enables it to perform either of these two common dung beetle tasks.

4. DISCUSSION

Two versions of a dung beetle-inspired robotic model are shown in this paper. They are based on measurements of a single dead dung beetle of the species *Geotrupes stercorarius* conserved in ethanol, meaning that the joints of the specimens were stiffer than those of the intact beetle. This forced the measurements to rely on manual movement of the dead dung beetle's joints, in order to see how the different joints and parts behaved. A source of error in this approach is the fact that the manual movement needs to be done with caution, in order not to overextend the joints to unnatural positions. Measurements including living or freshly dead dung beetles might yield an even more accurate model, that could also result in new discoveries.

Table 1 Coxa dimensions for all of the legs.

	Coxa		
	Front	*Middle*	*Hind*
Length [mm]	2.4	2.1	4.0
Width [mm]	1.6	1.6	1.6
Mass [mg]	1.2	1.5	3.0

Table 2 Femur dimensions for all of the legs.

	Femur		
	Front	*Middle*	*Hind*
Length [mm]	3.2	4.2	4.6
Width [mm]	1.8	2.0	2.4
Mass [mg]	2.8	2.2	2.6

Table 3 Tibia dimensions for all of the legs.

	Tibia		
	Front	*Middle*	*Hind*
Length [mm]	4.6	3.7	5.5
Width [mm]	1.0	0.9	0.9
Mass [mg]	1.5	1.3	2.1

Table 4 Body part dimensions.

	Body part		
	Head	*Thorax*	*Abdomen*
Length [mm]	4.5	5.1	9.0
Width [mm]	3.7	9.1	10.3
Height [mm]	2.9	4.3	4.0
Mass [mg]	14.8	23.8	30.4

Table 5 Accuracy test – deviation from the straight path – and speed test – straight distance walked (n = 45).

	Distance [cm]		Deviation [cm]	
Version Type	Mean	s.d.	Mean	s.d.
Approx. Version	12.44	0.19	0.07	0.10
Accurate Version	26.23	0.87	0.11	1.09

Table 6 Stability test – height deviation of the body (n = 45).

	Height [cm]	
Version Type	Mean	s.d.
Approx. Version	0.46	1.03e-3
Accurate Version	0.47	9.92e-4

Table 7 Distance rolled (n = 45).

	Distance [cm]		Deviation [cm]	
Version Type	Mean	s.d.	Mean	s.d.
Approx. Version	-	-	-	-
Accurate Version	3.23	3.24e-1	1.26e-3	2.33e-2

Another aspect to note is the fact that *Geotrupes stercorarius* does not roll a dung ball, but buries dung right away. One can discuss whether it is adequate to use a species with a limited amount of manipulation-related tasks. The kinematics should, however, be more or less similar for every dung beetle species and only the dimensions might differ. One could imagine that the hind legs of a species that roll a dung ball might be longer, which is a hypothesis based partially on observations of the African dung beetle (*Scarabaeus galenus*) that rolls and crawls on top of a dung ball.

The accurate dung beetle version is nevertheless able to achieve configurations that enable it stand on and roll a dung ball. This is most likely due to the complex kinematics and anatomy of the dung beetle leg, which emphasizes that the legs are not identical and instead split into three identical pairs, the hind, middle and front legs. These inequalities are somewhat expected since the hind legs play an important role in both locomotion and manipulation tasks, where the front legs are almost exclusively used for locomotion and digging purposes.

Due to the downwards orientation of the BC-joints, the legs of the accurate version can move in a parabolic trajectory (see Fig. 3A and 5) whereas the vertical orientation of the BC-joints in the simplified version only causes horizontal movement (see Fig. 3B and 1). The parabolic trajectory was initially hypothesised to have a negative impact on the stability and speed of the accurate version. This is, however, not the case: experiments revealed that the accurate version has a walking stability similar to the simplified version and that it is more than twice as fast. It is believed that this improvement is due to the fact that the accurate version is able to move its legs in parallel to the body at all times, where the simplified version moves its legs in a half sphere around its coxae. Furthermore, evolution has worked on perfecting itself for thousands of years and the dung beetle leg kinematics might be one of its perfections. Thus, in the case of a dung beetle-inspired hexapod, the usual approach of simplifying and enhancing the functionality of interest, with regards to locomotion, is not advantageous. However, if a consistent performance is of high priority, then the simplified version might be a better choice.

Finally, the extent of the approximations used in the model can be discussed. One of the largest approximations made in the accurate version is the removal of the tarsus. We believe, however, that the effects of this approximation are very small, but the actual performance impact will have to be investigated in future studies, as even the smallest detail might have a big influence on the emerging behaviour. Another approximation comes from the fact that the physical simulation used has a limited range of primitives. This is reflected in both the body and the legs of the two versions, which are composed of squares and cylinders, respectively. As a consequence of this the coxa – the yellow leg part – on the accurate version extends into the body of the model. This is due to the shape of the body, which on the real dung beetle is curved so that the coxa is aligned with the body. It is here important to note that these are mostly visual approximations, that are unlikely to affect locomotion of the model.

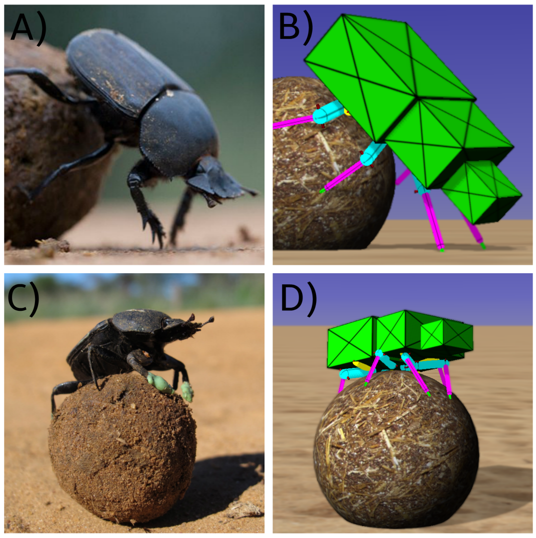

Fig. 6 A) A real dung beetle ready to roll a dung ball (modified from [18]) . B) The accurate version ready to roll a dung ball C) A real dung beetle on top of a dung ball (modified from [19]). D) The accurate version on top of a dung ball.

5. CONCLUSION

This study has demonstrated a method for investigating the kinematics of a dung beetle. From these measurements accurate and simplified versions of a dung beetle have been simulated for the purpose of comparing their multifunctional abilities. The accurate version uses a minimum of approximations, where as the simplified version only focuses on the locomotion and is thus allowed rather large approximations.

It was found that the accurate version outperforms the simplified one with regards to both walking speed and multifunctionality. However, the accurate version is also more cumbersome to create in simulation, due to the need of an initial biological investigation and the more complex kinematics model. Besides the multifunctionality and improved speed, the accurate version also enables us to get a deeper understanding of a dung beetle, since it elicits behaviors comparable to those of the real beetle when the modified version of the WALKNET controller was used [15].

Therefore, when developing a dung beetle-inspired model it can be advantageous to do it without simplifications, as they may – indirectly – influence the functionality of interest. Another suggested benefit is the ability to use the legs for both locomotion and manipulation, like the real dung beetle, which most bio-inspired hexapods with simplified leg kinematics are unable to do. Finally, these findings may also apply to other bio-inspired robotics. This needs to be investigated in future studies.

6. ACKNOWLEDGEMENTS

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