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Test Benches for Comparing the Performance of an Ant's Leg with a Hexapod Robot's Leg

Ilya Brodoline, Pierre Moretto, Stéphane Viollet,
Vincent Fourcassié, and Julien R. Serres

Animal-inspired mobile robots tend to show remarkable performance in outdoor locomotion and navigation tasks, but a big gap remains between robots and animals in terms of autonomy and endurance [1]. Biomimicry is helping to solve numerous design issues through a better understanding of how animals move. Insect-inspired robots, in particular, can be built to interact with uneven terrains which are difficult to traverse for other robots [1], and bio-inspired robots designed to overcome the technological limitations of artificial systems are also valuable models for biologists in better understanding the behavior of animals [1], [2]. Therefore, exploring the limitations caused by mimicking insects of a few millimeters with robots measuring several centimeters becomes relevant. In this study, we first present two test benches used to investigate leg movement: one used to characterize that of an ant and the other that of a robotic leg. By comparing this multiscale data, we discuss the significance and relevance of these measurements in evaluating the robotic performance.

Walking Performance of a Millimeter-scale Ant

Motion Capture System

During the last decade, huge progress has been made in the development of efficient motion capture systems for the study of human movements, and several such systems are already commercially available. These systems are perfectly suitable for the study of humans and other big vertebrates that can be equipped with reflecting markers, and whose position can then be automatically tracked at a high frame rate. However, the use of such markers is virtually impossible when working with small organisms such as insects whose body length rarely exceeds one centimeter. This makes the tracking of particular points on their body a challenging task, and one has to resort to sophisticated image analysis software to pinpoint and track specific anatomical points in the sequences of images acquired from the videos. The execution of movements in insects can be extremely rapid, so the study of movement in these organisms

often requires the use of special equipment such as ultrahigh-speed cameras. Because of these constraints, all studies of insect movement published so far have relied on custom made equipment rather than on commercial systems. Limitations to the optical resolution of video equipment also explain why most studies of insect movement have, for a long time, only been achieved on larger insects such as cockroaches or stick-insects. It is only recently that studies of limb movements on small insects such as the model organism *Drosophila* have begun to appear in the literature [2].

Among all insects, ants offer relevant biological models for the building of bio-inspired legs for hexapod robots. With more than 12,000 species identified so far, ants are one of the most diverse groups of insects and are characterized by an amazing variety of morphologies, both within and between species [3]. Moreover, they can be found in all types of biotopes. As a result, their locomotor equipment, locomotor behavior and musculoskeletal system have evolved outstanding adaptations, allowing them to run at extreme speed, to crawl through narrow tunnels, to climb vertical surfaces and even to swim, jump or glide in the air. Finally, ants are one of the rare organisms in the animal kingdom that can walk distances several thousand times their body length while carrying loads exceeding their own by up to 15 times.

To study the kinematics of locomotion and leg movement in ants we used a custom-made setup designed by a private company (Fig. 1). The setup was designed by a private company (R&D Vision, France. <http://www.rd-vision.com>) and is described in [4]. The ant, as it moves on a horizontal walkway, is filmed by five synchronized cameras (JAI GO-5000M-PMCL: frequency: 250 Hz; resolution: 30 $\mu\text{m}/\text{pixel}$) equipped with 16 mm macro lenses (Fujinon CF16H1-1). Four cameras are positioned laterally to, and one vertically above the walkway. Four infrared strobe spots ($\lambda = 850 \text{ nm}$), synchronized with the cameras, illuminate the walkway from above and allow a better contrast between the ant and the background. Individuals of the ant species we studied (*Messor barbarus*) vary in body length (distance between the tip of the abdomen and the bases of the mandibles) from 0.9 to 6 mm. Our setup

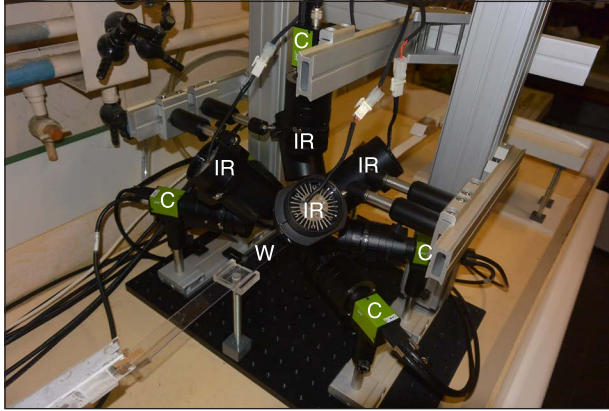


Fig. 1. Setup used for the study of the kinematics of ant locomotion. C=camera; W=walkway; IR=infrared strobe.

has been calibrated to record their locomotion in a 20x20x250 mm volume with a 0.0096 mm/pixel resolution, with on average, 3% (i.e., 0.03 mm error on a 1mm measure) resolution in each dimension of the volume (including tracking and pattern recognition errors). The locations of 47 anatomical marks for body extremities and articulations between the different body segments (Fig. 2d) were then determined in an external 3D coordinate system using the software Vicon Peak Motus 10.0 (<http://www.motus10.com/>). Since the number of points we

tracked on the ants was significant, and the videos were captured at a high frame rate (250 Hz), this tracking process can be extremely time-consuming. The recently developed deep-learning based approach to automatically track points looks very promising for reducing the time dedicated to the tracking of insects' anatomical marks [2].

Unfortunately, at the end of the experiment, it was necessary to humanely kill the ants so that the mass of their three main body segments (head, thorax, and gaster) could be measured. With this information and the positions of the extremities of those segments, the position of the center of mass (CoM) for each ant could be approximated. This allowed us to study the dynamics of the overall CoM of the ants in different conditions, e.g., when an ant is walking unladen or bearing a load in its mandibles [5]. Based on high resolution images of the ant exoskeleton acquired through X-ray microtomography, we were then able, by using the free open source software Opensim (<https://opensim.stanford.edu/>), to characterize the different types of articulation between body segments and between the parts of the legs, and to integrate this information into a 3D ant kinematic model. Using an inverse kinematic optimization process, this 3D model subsequently allowed us to reduce the errors due to tracking and pattern matching recognition [6]. By considering an ant as a polyarticulated system composed of 40 articulated solid segments, one can then

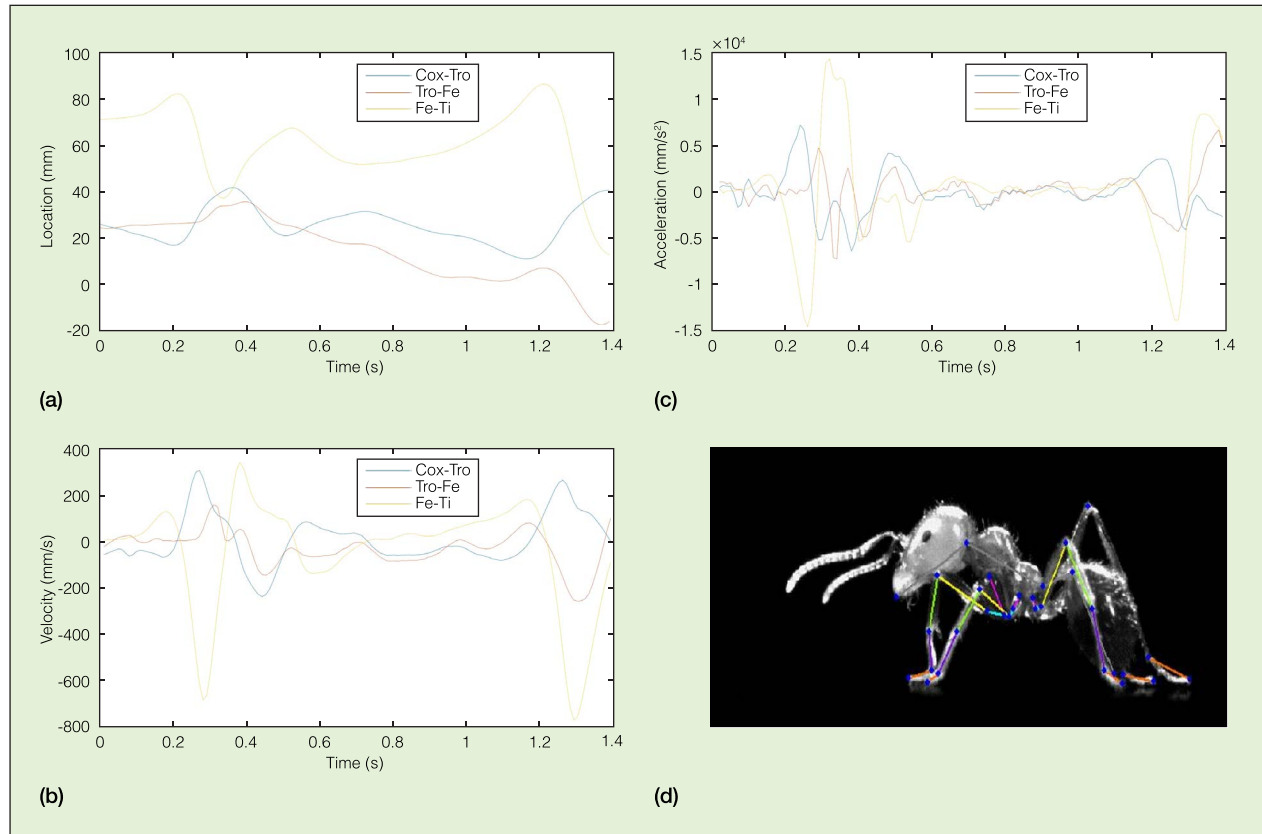


Fig. 2. (a) Vertical position of the joints in the 3D ant kinematics of the middle leg over time; (b) Vertical velocity of the joints; (c) Accelerations of the joints; (d) Segments and joints are computed in the external frame using a kinogram. Cox-Tro= coxa to trochanter joint; Tro-Fe= trochanter to femur joint; Fe-Ti= femur to tibia joint.

calculate several kinematic parameters such as the segment positions and joint angles and their derivative as a function of time, i.e., the linear and angular velocities and accelerations (Fig. 2) [6].

Walking Performance of a Centimeter-scale Hexapod Robot

In this study, we focused on relatively small hexapod robots that weigh about 2-3 kg and have a maximal body span of one meter. These dimensions are constrained by the size and performance of commercial electric servomotors, such as the *Dynamixel AX-18A* presented here. At this scale, the conventional structure of a robotic leg is presented in Fig. 3. To facilitate construction, reduce energy expenditure and simplify control, the robotic leg is composed of three segments compared to the five main segments of a real insect leg (Fig. 3) [1].

The characterization of a robotic leg (or a hexapod robot) lacks a proxy, and thus the quantification of each level of performance is not well defined within the robotic community. However, such proxies deserve to be rigorously defined for future comparisons between robotic designs. Few test benches for hexapod robots have been built [7]. This test bench (Fig. 4) includes the measurement techniques of insect performance to define a unique experimental setup that provides access to meaningful indicators for legged robotics. Thus, this universal setup provides a complete set of data, appropriate for estimating any characteristics of a chosen robotic leg.

The test bench is composed of four modules:

- A vertical one-axis moving stage with an instrumented treadmill: these two components simulate the robot walking movement. Since we study only a single leg, the movement of the ground relative to the robot's body is represented by the freewheel treadmill and the vertical

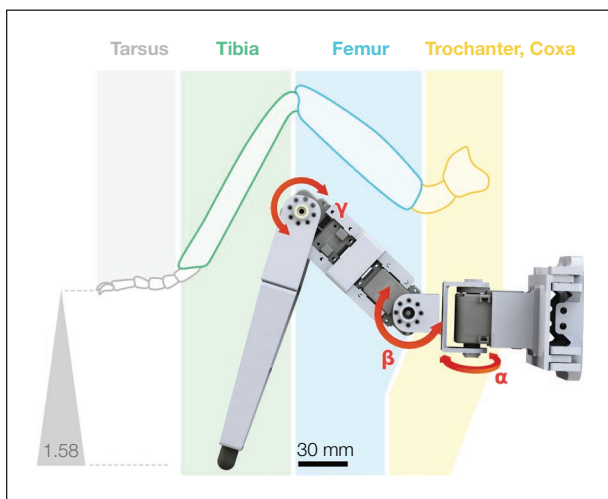


Fig. 3. Conventional leg of a hexapod robot equipped with 3 degrees of freedom, inspired by the *Messor barbarus* ant (scale 1:58). Angle α corresponds to the thorax-coxa joint position, angle β corresponds to the trochanter-femur joint (thus far, robotic designs have often fused the coxa-trochanter joint), and angle γ represents the femur-tibia orientation.

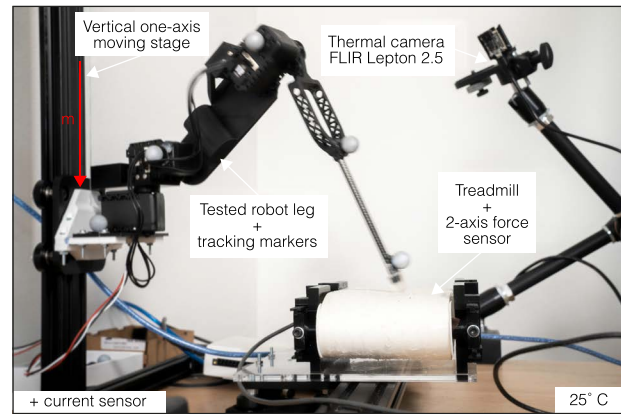


Fig. 4. Dedicated test bench to evaluate any robotic leg. The bench allows the leg to "walk" on a treadmill simulating the terrain displacement. Photography by Tifenn Ripoll—VOST Collectif / Institut Carnot STAR (2021).

body oscillations [8] by the moving stage. To limit vertical oscillations, a mechanical stop is implemented to prevent the leg from hitting the ground during the swing phase. The contact force of the leg's tip is measured by a 2-axis force sensor.

- A three-dimensional motion capture system (Qualisys™, Sweden. <https://www.qualisys.com/>) provides the kinematics of the leg joints and segments during a walk phase.
- An electrical current sensor and tangential and normal treadmill force sensors are used to estimate the consumption of both electrical and mechanical energy. It is noteworthy that the normal force measurement is provided by four force sensors covered by an aluminum plate, the bearing surface.
- A thermal camera provides an overview of the leg's structural weaknesses, the efficiency of thermal dissipation and energy loss. Furthermore, ambient temperature is measured by this camera, providing experimental repeatability and highlighting temperature dependent leg performance indicators. The leg can be loaded by a mass m , and the room is maintained at 25 °C (Fig. 4).

Typically, the tested leg walks on a treadmill for a fixed amount of time (15 min), with the sensors capturing data which, at the end of the session, are processed to extract desired characteristics (Table 1).

Crossing Multiscale Data, Comparison Between Animal and Robotic Measurements

Table 1 presents the results obtained from measurements carried out on a *Messor barbarus* ant and the hexapod robot leg (Fig. 3). The values grouped in the table form a standard set of indicators used for the comparison of the robotic leg with its animal counterpart or that of another robot. A scale factor has been added to relevant indicators, which allowed us to compare two agents of different body scales [9]. To compare an ant's performance indicator with that of the robot, we have to

Table 1 – Comparison of the specifications of an ant walking at its spontaneously chosen speed to those of an analogous hexapod robot

Indicator	Ant	Scale factor $\alpha = 1:58$	Hexapod robot (ant's values scaled to the robot's size)
Total mass	8.92 mg	α^3	2 kg (1.7 kg)
Middle leg segment length (mm)	Coxa-trochanter: 0.4 Femur: 1.6 Tibia: 3	α	Coxa-trochanter: 40 (23) Tibia: 95 (93) Femur: 178 (174)
Speed (cm/s)	0.4	$\alpha^{1/2}$	21 (3)
Stride length (mm)	5.7	α	265 (330)
Stride frequency (Hz)	0.7	$\alpha^{-1/2}$	0.8 (0.09)

multiply the ant's indicator value by the associated scale factor to estimate the same indicator for the robot.

Numerous other parameters exist, not presented in Table 1, which characterize the walking performance of an insect or a robot [10], either unrelated to both the robot and the animal or which are hard to evaluate for one of the two. One example of this is the cost of transport (CoT) [1], a typical estimation of the energy needed to move an agent at a specific speed and with a given load. For a robot it is defined as a dimensionless value easily measurable at the power supply input. For hexapod robots based on *Dynamixel* servomotors, the CoT values is usually between 1.5 and 6.2 [1]. When it comes to biology, the CoT is frequently defined in joules per kilogram-meter and requires an estimation of the metabolic rate [11], which is difficult to evaluate for an ant measuring only a few millimeters. An ant's CoT is estimated at a value of 39 [1], but it depends on the ant's weight and measurement conditions [11].

Table 1 ant's scaled parameters suggest that a robot is able to exceed the parameters measured in our *Messor barbarus* ant walking at its spontaneously chosen speed. Our robotic leg is able to generate higher speeds of up to 38 cm/s, defined by the chosen actuator specifications (ours has a maximum speed of 97 rpm and is one of the highest for a servomotor of this category). However, the ant's speed can reach up to 86 cm/s [12], leading to the conclusion that robot performance limits are still below those of the animals.

As shown on Fig. 5b, the implemented leg tip path conserves the continuity of speed and acceleration, inherited from the ant's kinematics, despite the resizing. Nevertheless, the contact of the robot's leg with the ground is highly disturbed (Fig. 5c) and an increase in the error is observed after high acceleration phases. These variations in the error value are primarily caused by the high inertia of the robot leg, and secondly by robot imperfections [1]: motor heating, friction, mechanical backlash and leg stiffness.

Taking into account the limitations of bio-inspired robots, are there any benefits to using robots, instead of simulated insect multibody models? As shown by the hexapod robot experiments of the last decade [1], the development of insect inspired robots is mainly motivated by the study of real insect locomotion, navigation, or visual sensory systems. It

is still rare to see dynamics hypotheses proven by hexapod robot studies, due to drawbacks inherent in robot mechanical systems. The development of new and more realistic robots, closer to biological structures, should soon begin to overcome these drawbacks. Currently, the dynamic properties observed in insects, i.e., energy recovery during walking [8], limb elasticity and compliance [8], are more likely to be implemented in robots and constitute essential features of insect legs that are rarely present in conventional hexapod robot legs but which appear meaningful for walk stabilization.

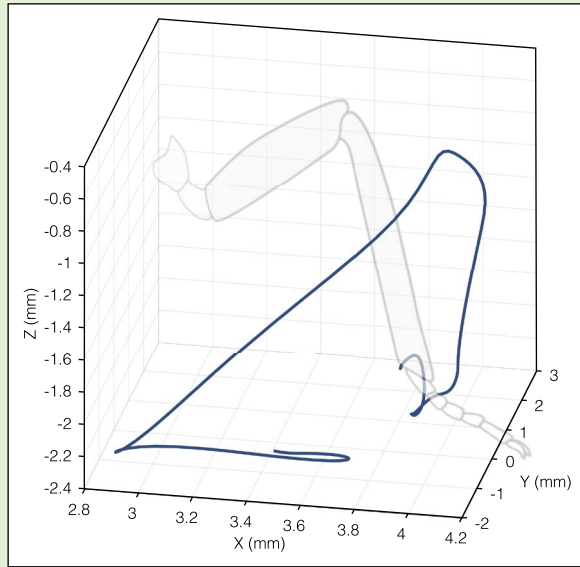
Conclusions

A bio-inspired robot usually takes a specific animal as a model, so designing a bio-inspired hexapod robot whose size is about 58 times that of an ant (10 mm) could appear, at first glance, inconsistent, even if mimicking observations at a larger scale appears tempting. This study focuses on two data sets collected from two test benches: the first used to characterize the walk of an ant, and the other to test the performance of a conventional artificial leg often used in bio-inspired robotics research.

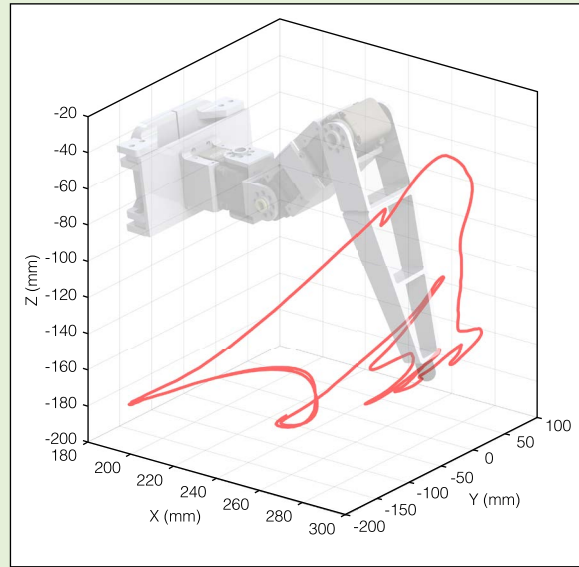
In addition to robotic applications, our test benches could be used to deduce hypotheses about the dynamic behavior of ants, such as the intra-leg coordination or the coordination of its six legs during its locomotion. From a robotics point of view, test benches are useful for extrapolating the energy consumption of a legged robot from a single leg and therefore increasing their navigation distance, a prerequisite for the implementation of a navigation system based on bio-inspired visual sensors. In conclusion, this study is a first step towards understanding how biological data from ant locomotion can be used in hexapod robotics.

Acknowledgment

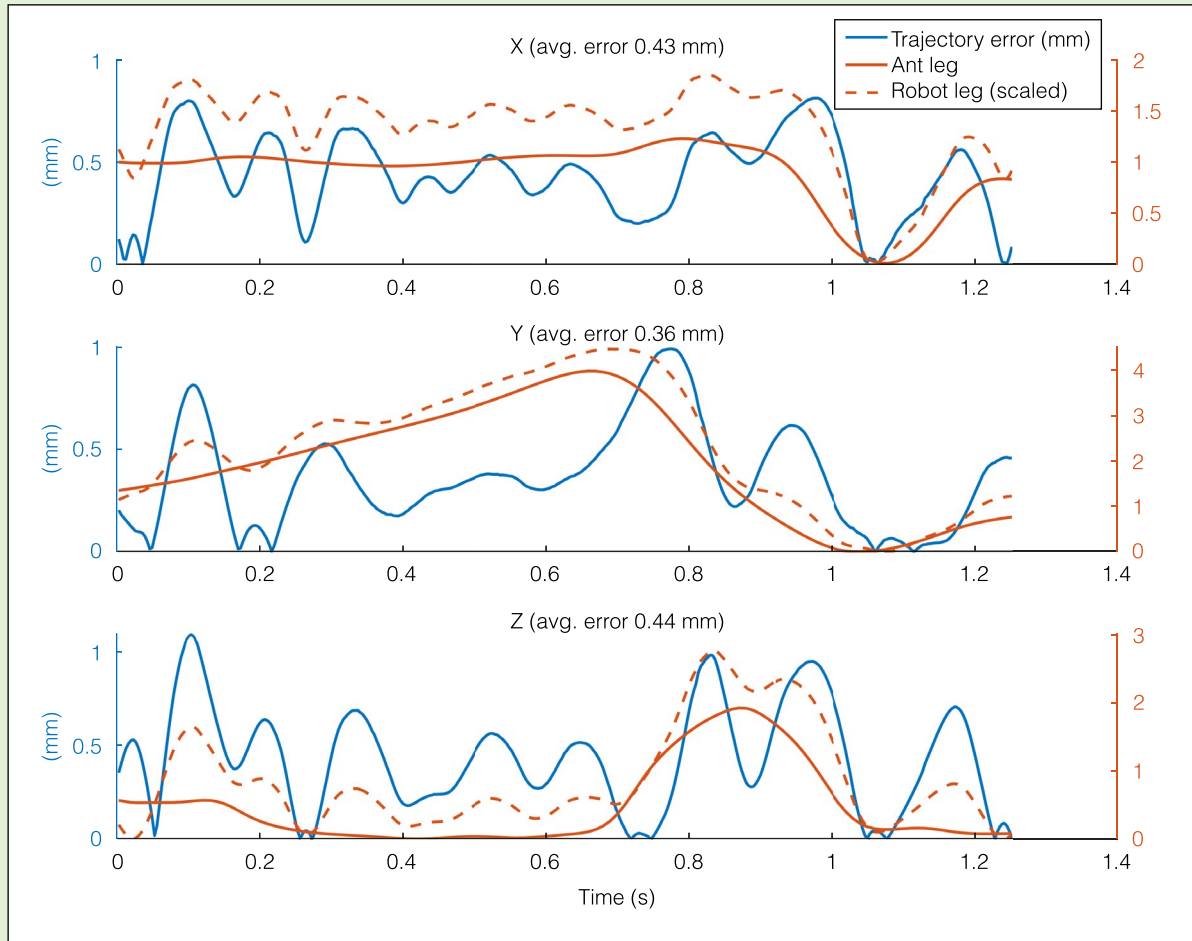
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(a)



(b)



(c)

Fig. 5. (a) Trajectory of the ant's middle leg tarse during one walking cycle; (b) Trajectory of the tip of a robot leg with three degrees of freedom, following a path obtained from the ant's middle leg data as an inverse kinematics input, at a scale factor of 1:58; (c) Error of the scaled down (i.e., to the ant's length) robot leg position regarding the implemented ant's leg trajectory.

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I. Brodoline (ilya.brodoline@univ-amu.fr) is a Ph.D. degree Student in the Biorobotics team at Aix Marseille University, with the National Center for Scientific Research (CNRS), Institute of Movement Sciences, Marseille, France. He received his M.Sc. degree in mechatronics engineering from the École Nationale Supérieure de l'Electronique et de ses Applications (ENSEA), Cergy, France. His research interests include legged robot design, actuation systems, integration of sensing into mechanics, and fast prototyping.

P. Moretto (pierre.moretto@univ-tlse3.fr) joined the Animal Cognition Research Center (CRCA-UMR UPS-CNRS 5169) Collective Animal Behavior Team at the National Center for Scientific Research (CNRS) in Toulouse, France and is developing biomechanics at the insect scale and studying collective and collaborative behaviors. He received his Ph.D. degree in physiology and biomechanics of human movement in 1993 and was Assistant Professor until 2009 at the University of Lille 2 until 2009, when he joined the University of Toulouse III – Paul Sabatier as a Full Professor of biomechanics. He has supervised numerous academic and industrial research projects and has significant experience in biomechanics, motor control and the optimization of human and animal locomotion.

S. Viollet (stephane.viollet@cnrs.fr) is Research Director at the National Center for Scientific Research (CNRS) and currently runs the Biorobotics Laboratory in the Institute of Movement Sciences, Aix Marseille University, Marseille, France. His research interests include biorobotics, sensorimotor control as well as the development of innovative bioinspired visual sensors and control laws for implementing autonomous robots. He received his M.Sc. degree in control engineering from the University of Bordeaux 1 and the Ph.D. degree from the National Polytechnic Institute, Grenoble, France in 2001. In 1997, he joined the Biorobotics Research Group, Marseille, France, as a Ph.D. degree Student.

V. Fourcassié (vincent.fourcassie@univ-tlse3.fr) is Research Director at the Center of Integrative Biology, Research Centre on Animal Cognition in the National Center for Scientific Research (CNRS), Toulouse, France (CNRS). His research deals with insect behavior, in particular social insects, insect biomechanics and ant biology. He received a Ph.D. degree from the University Toulouse III – Paul Sabatier, France in 1988. After several years as a postdoc (Boston University, Free University of Brussels, University of Leeds), he returned to University Toulouse III where he obtained a position as CNRS Research Associate in 1994.

J. R. Serres (julien.serres@univ-amu.fr) has been a Senior Lecturer at Aix Marseille University since 2014 and is a member of the Biorobotics team at the Institute of Movement Sciences, Marseille, France. He will be a senior member of the Institut Universitaire de France (IUF) in Paris, France from 2022 to 2027. His research interests include bio-inspired robotics and bio-inspired visual localization techniques.