

Drosophibot: A Fruit Fly Inspired Bio-Robot

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Abstract. We introduce Drosophibot, a hexapod robot with legs designed based on the Common fruit fly, *Drosophila melanogaster*, built as a test platform for neural control development. The robot models anatomical aspects not present in other, similar bio-robots such as a retractable abdominal segment, insect-like dynamic scaling, and compliant feet segments in the hopes that more similar biomechanics will lead to more similar neural control and resulting behaviors. In increasing biomechanical modeling accuracy, we aim to gain further insight into the insect's nervous system to inform the current model and subsequent neural controllers for legged robots.

Keywords: Insect robot \cdot Fruit fly \cdot Dynamic scaling \cdot Passive compliance

1 Introduction

Legged robots have been a key focus of robotic design for many years due to their promising capacity for mobility. While wheels or treads are easier to design and control, multi-legged robots in particular would be able to traverse far more complex terrains with greater robustness and maneuverability, making them valuable for a variety of exploratory and autonomous applications [8]. In regards to implementing legs, animals, and insects in particular, provide excellent models for legged locomotion over difficult terrains (for a review, see [3]). They are able to traverse punishing landscapes with speed and agility, and can quickly compensate to maintain efficient movement if legs become injured or lost by altering their stance and stepping pattern [1]. Fruit flies are particularly interesting for biologically inspired robotics due to the abundance of genetic tools available to manipulate their nervous systems. Examples include studying the neural control of locomotion in mutants that lack different neuromodulators and using light-activated ion channels to selectively deactivate proprioceptors in the legs during walking [11,22]. Experiments like these have huge potential to thoroughly explain the neural control of walking in insects in general and fruit flies

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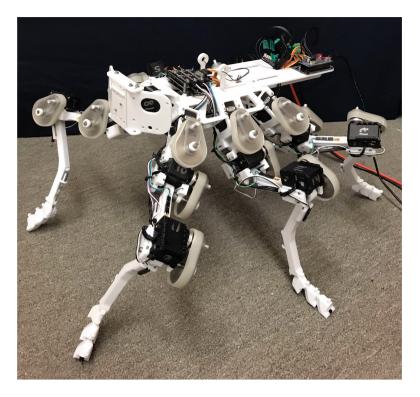


Fig. 1. An assembled view of Drosophibot standing on six legs

in particular. Thus, to more directly apply these and other findings from fruit fly locomotion, we present Drosophibot, a hexapod robot with several key fruit fly-like characteristics (Fig. 1).

Our previous robot, MantisBot, provided significant insight and impetus for the design of Drosophibot. MantisBot is a 28 degree-of-freedom legged robot designed to mimic the dimensions and movement of a Chinese mantis, *Tenodera sinensis* [18]. The robot was used as a testing platform for a variety of biologically-inspired insect-like neural control networks [18–20]. While it was successful in some such testing, our design for Drosophibot seeks to improve four main characteristics of MantisBot:

- 1. Higher strength-to-weight ratio;
- 2. More animal-like distribution of weight;
- 3. More similar dynamic scale to that of an insect; and
- 4. Compliant tarsus-like feet that may be used to study substrate grasping reflexes

The decision to exclude some of these components in MantisBot is in-line with many other contemporary insect-like bio-robots, and all of these robots successfully fulfill their design goals. Ensuring a sufficient strength-to-weight ratio is

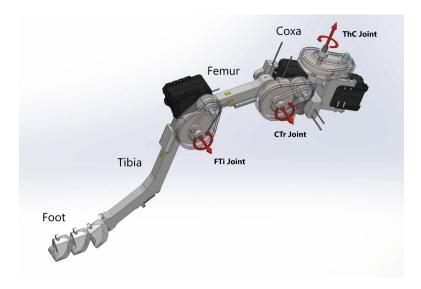


Fig. 2. A labeled schematic of Drosophibot's leg with axes of joint rotation and strain gauges in gold

a common design problem in legged robots and has been solved by including a spring in parallel with actuators [21], as we do in this study. Drosophibot's parallel springs enables it to support more weight, while simultaneously mimicking the passive forces of insect joint membranes [2,10] and helping to dynamically scale Drosophibot to be more similar to the insect. To our knowledge, no previous insect-like robot has explicitly addressed dynamic scaling of the robot relative to the animal. In addition, to our knowledge, no previous robots have addressed adhering to a more animal-like distribution of weight; robots such as OCTAVIO and HECTOR do not include the abdominal segments possessed by their insect inspirations in their designs, presumably to reduce the total body weight [9,14,21]. Last, legged robots do not typically include compliant feet in their designs, as they add complexity and are not totally necessary for stable locomotion. However, they add valuable compliance during walking, as well as a higher fidelity insect model [4,15,21].

In this manuscript, we describe the technical design of Drosophibot, including its electronics and mechanics. We include sections for each of the four aforementioned aspects that we sought to improve from MantisBot, describing the manners in which they are addressed in the design. Some preliminary electromechanical tests are presented to showcase the underlying capabilities of the robot, then we conclude by previewing the future uses of Drosophibot as a neural testing platform.

2 Overview of Design

Drosophibot's legs and body are designed based on the common fruit fly, Drosophila melanogaster. Each leg has three actuated joints (Fig. 2); the thoraxcoxa (ThC) joint moves the leg forward and backward, the coxa-trochanter (CTr) joint elevates and depresses the leg, and the femur-tibia (FTi) joint extends and flexes the tibia segment. One additional servo attaches to the front of the thorax to actuate the head, totaling 19 degrees of freedom (DOF) throughout the robot. The included three DOF per limb comprise the minimum for movement in 3D space, and were selected due to their established role in insect locomotion and their usefulness in other insectoid robots [14,21]. We omitted any additional DOF in the insect to decrease complexity, as well as the lack of available data concerning their specific functions. Each leg also possesses three tarsal segments, which are passively actuated via an elastic tendon. All of the legs are homologous, each actuated by Dynamixel AX-12 smart servos (Robotis, Seoul, South Korea) with a stall torque of 1.5 Nm at 11.1V. The smart servos were selected over fluid actuated tendons or transmissions primarily for their simpler, strictly linear control scheme and the simplifications of the mechanical design they allowed.

Each leg has three strain gauges: two mounted on the trochanterofemur (anterior [Group 2] and dorsal [Groups 3 and 4] [24]), as well as one on the tibia (dorsal [Group 6A] [23]), to detect the strain of each leg during locomotion. Strain sensors in insects have long been known to work in conjunction with force sensors built into the muscle-apodeme complex, so strain gauge data combined with torque data from the servos will provide a useful analog for simulation [23].

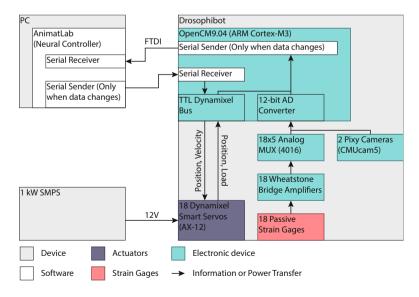


Fig. 3. A diagram of Drosophibot's electronics and control system

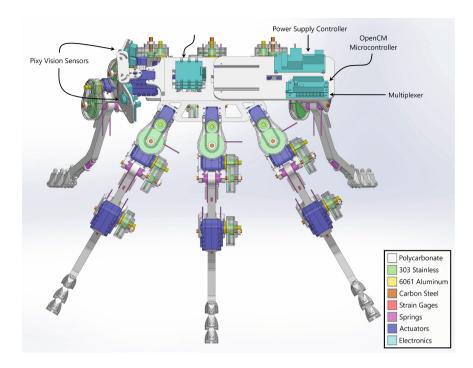


Fig. 4. A side view of Drosophibot with materials, springs, sensors, actuators, and electronic components color-coded.

Load signals from the strain gauges are amplified by custom Wheatstone bridges, which in turn interface with an OpenCM9.04 microcontroller (Robotis, Seoul, South Korea) via a 12-bit analog-to-digital converter. The OpenCM9.04 also sends position commands to the servos and reads their position and torque with a 1 MHz baud rate. The OpenCM9.04 functions as a serial tosser, communicating with a desktop computer via a USB serial connection. The desktop computer runs the neural controller in AnimatLab [6]. The robot's head also includes two Pixy (CMUcam5) cameras for recognizing specific colors in the environment. Figure 3 shows a diagram of the electronics and control system.

2.1 Strength-to-Weight Considerations

For needed strength, each servo includes additional gearing to double the output torque. The resulting strength-to-weight ratio is still less than that of the insect, but sufficiently accomplishes our stated goal of improving upon MantisBot's ratio to achieve walking capabilities. As this goal was the only considered during actuator selection, the Dynamixels would likely prevent the system from ever matching the ratio of *Drosophila*. The vast majority of the structural components are made of extruded polycarbonate, with some parts out of 6061-T6 aluminum. All gears are made out of 303 stainless steel and rotational shafts out of carbon

steel. Figure 4 shows a color-coded view of the different materials and electronics that make up the robot.

2.2 Abdominal Segment for Weight Distribution

To more accurately mimic *Drosophila's* biomechanics, Drosophibot also includes an adjustable abdominal segment which houses all controllers and additional weight to achieve the insect's center of mass (COM). The COM of *Drosophila melanogaster* is approximately 1/10 of the length of the thorax behind the middle set of legs [16]. This bias is the result of the insect's abdominal segment making up the majority of its mass. By contrast, Drosophibot's actuators comprise the bulk of its mass, heavily biasing the COM to the middle of the thorax. The simplest way to shift this bias toward the rear is to add mass to the rear of the thorax; however, adding too much mass then risks making the entire robot too heavy for the Dynamixels. Therefore, the adjustable abdominal feature enables us to increase the impact of any added mass in redistributing the robot's COM, allowing us to more closely match the distribution of the animal with an acceptable amount of weight for the servos.

2.3 Dynamic Scaling

We placed torsion springs in parallel with all leg joints, such that the spring resists the servo's torque when raising the leg, and assists the servo in supporting the body weight throughout the stance phase. These springs additionally mimic the elastic forces in the legs of small animals in general, which shifts the animal's control strategy from one based on momentum, as in larger animals such as humans, to one more reliant on kinematics [10].

Matching the scaling in this way requires that the ratio between passive stiffness and inertia be the same for Drosophibot as in *Drosophila*. Figure 5A shows a simplified diagram for the CTr joint. This includes a torsional spring with stiffness k_T and the mass of the FTi actuator, m, located distance L from the joint. Figure 5B shows the associated free body diagram. Assuming that the joint angle θ is small, we can analyze the deflection of the mass in the x direction.

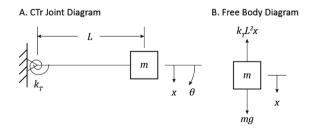


Fig. 5. A. Simplified functional diagram of the CTr joint with the parallel spring, the limb's mass, and the limb's length labelled. B. The associated free body diagram.

To do so, we calculate the equivalent linear spring stiffness $k_{eff} = k_T/L^2$. This enables us to write the equation of motion for this simple system,

$$m\ddot{x} = mg - \frac{k_T}{L^2}x. (1)$$

Since the acceleration of gravity is scale-invariant, we can solve this equation for g, and use the resulting expression as a constraint on the inertia, length, and stiffness of the robot to ensure its dynamics are like those of the fly:

$$\ddot{x} + \frac{k_T}{mL^2}x = g. (2)$$

This result is consistent with the finding in [10] that the ratio between a limb's stiffness k_T and its moment of inertia $I = mL^2$ defines the control regime that an animal must use (i.e. momentum- or kinematics-based). Thus, our constraint equation is

$$k_{\text{robot}}/I_{\text{robot}} = k_{\text{flv}}/I_{\text{flv}}.$$
 (3)

Direct measurements of these quantities in the fruit fly are not available, but we can estimate them using measurements from other insects. In stick insects, the calculated joint stiffness is 10^{-6} Nm/rad [10]. Since muscle stiffness is proportional to the cross-sectional area squared, and a fruit fly is about 1/10 the scale of a stick insect, a fly's muscle's stiffness should be 1/100 that of a stick insect. In addition, the lever arm of the muscle is 1/10 as long, so this scales the muscle stiffness again by 1/100. The resulting joint stiffness of a fruit fly due to passive muscle forces should be about 1/10,000 that of a stick insect, $k_{\rm fly} = 1 \times 10^{-10}$ Nm/rad. This does not include passive forces from the joint membranes of the exoskeleton, which are also known to contribute substantially to passive joint forces [2,10].

The fruit fly's leg is about 1 mm long, and has a mass of about $24\,\mu g$, which is 2% of its total mass of $1.2\,mg$ [16,22]. Its moment of inertia should be on the order of $I_{fly}=24\times10^{-15}~kgm^2$. We experimentally measured the moment of inertia of one of our Dynamixel AX-12 servos by using an unpowered unit as the hub of a large pendulum. We approximated the servo's moment of inertia and damping by measuring the pendulum's response, and then subtracting the inertia of the pendulum. Due to the servo's large gear ratio (508:1) and the small mass of the plastic legs, the majority of the leg's inertia comes from the servo's rotor. We experimentally measured this value to be $4.0\times10^{-3}~kgm^2$. The resulting target stiffness for the servo to replicate the dynamics of the fruit fly is

$$k_{\text{robot}} = k_{\text{fly}} I_{\text{robot}} / I_{\text{fly}} = 1 \times 10^{-10} (4 \times 10^{-3}) / (24 \times 10^{-15}) = 16 \text{ Nm/rad.}$$
 (4)

Since the servo and the springs are in parallel, their stiffness adds. Each joint has two springs, each with a stiffness of $0.307~\mathrm{Nm/rad}$. The servo's stiffness, when set to its most compliant setting, is $9.17~\mathrm{Nm/rad}$. Therefore, the total joint stiffness is $9.78~\mathrm{Nm/rad}$, near to that of a fruit fly, and much greater than

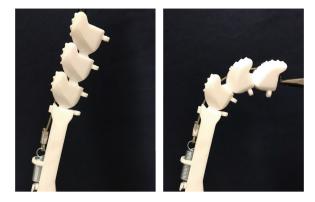


Fig. 6. Foot at its neutral position (left) and at maximum rotation (right)

that of a stick insect. We can further tune the stiffness of the joints by increasing the gain of the position feedback in the servo's controller. In this way, we can ensure that Drosophibot is dynamically scaled correctly and, therefore, is better suited as a test platform for testing for controllers based on nervous systems.

2.4 Compliant Feet

To further increase the fidelity of biomimicry of Drosophibot, we chose to add compliant foot segments. The design for MantisBot simply includes pointed tips at the bottom ends of the tibias to press into the ground, which makes walking on smooth, hard surfaces difficult. Other recent insectoid bio-robots circumvent this problem by including suction cups, rubber surfaces, and inline passive springs for better grip, but the robots are still functionally walking on the stubs of their tibia segments [9,14,21]. This lack of a dedicated foot segment or tarsus causes issues in replicating accurate biological motion, as most insects have fairly long tarsi, with *Drosophila's* foot segment measuring almost the same length as the tibia. Without feet, bio-inspired robots' torsos sit much closer to the ground, potentially causing collisions of the torso with the ground, and certainly leading to kinematics differing from the corresponding animal's. Additionally, a robot with compliant feet would have greater contact area with the ground and lower impact loading when a leg enters stance phase due to the elasticity of the feet, which should prolong the life of the actuators and the load-bearing components.

With these factors in mind, Drosophibot includes compliant feet that mimic those of *Drosophila* and other insects. Each foot is made up of a series of segments interconnected with a limited ball-and-socket joint and attached to an additional angled segment of the tibia. Thin wire cable routes through the underside of each segment and attaches to an extension spring mounted on the tibia to provide a restoring force throughout the ground contact deformation shown in Fig. 6. The morphology of the tarsal segments was loosely based on the tarsal shape present in *Drosophila*, while also maximizing ground contacting surface area.

Cleats were additionally added to these surfaces for better grip on the carpeted testing surface. Three tarsal segments have initially proven to provide the desired level of ground contact with minimal complexity.

3 Results

Several "proof of life" tests have been conducted on Drosophibot thus far to validate our calculations of its electro-mechanical capabilities. Most of the initial tests have involved validation of the strength-to-weight ratio of the robot, in particular the temperature behavior of the servomotors over time. This allowed us to confirm the expected capabilities of the robot and determine if there were any time constraints for testing relating to servomotor overheat. Figure 1 shows the robot standing on its six legs. Figure 7 shows the results of tests involving the robot standing on six and three legs, monitoring the average temperature at each load bearing servomotor over the span of 30 min, or until a servomotor surpassed the maximum operating temperature of 70 °C. For both tests, the center of mass of the robot was shifted to the biologically accurate position with the additional abdominal mass. Through these tests, we have also determined the read/write bandwidth to control all six legs as 44 ms.

We have also conducted center of mass tests with the robot suspended to confirm that an additional abdominal mass of 700 g sufficiently shifts the center of mass to within the desired location behind the middle set of legs. While no quantitative tests have yet been conducted specifically on the robot's tarsal segments and dynamic scaling, they show great improvements to the corresponding design of MantisBot.

4 Discussion

4.1 Interpretation of Temperature Data

In both sets of strength-to-weight validation testing, the temperature of the load bearing servomotors stabilized at a level at minimum 3° below the maximum operating temperature, in most cases well below this value, over the course of 30 min. The temperatures of the loaded legs also appear relatively unaffected by the number of legs involved in the stance, and in some cases stabilized at lower temperatures when in the three leg stance. This data proves promising in utilizing the robot for prolonged testing periods of 30–45 min, which MantisBot was previously not capable of. Additionally, these tests validated the usefulness of the equilibrium position in each joint between the springs and robot mass in servo cool-down, as the joints arbitrarily placed near their equilibrium exhibited temperatures close to ambient for the servo, and were able to stay relatively cool if perturbed while near equilibrium as in the case of the Right Front FTi joint in the three leg stance. This will prove useful in further extending the operating time of the platform by adding a cool-down procedure into the control when the system detects a joint getting too hot.

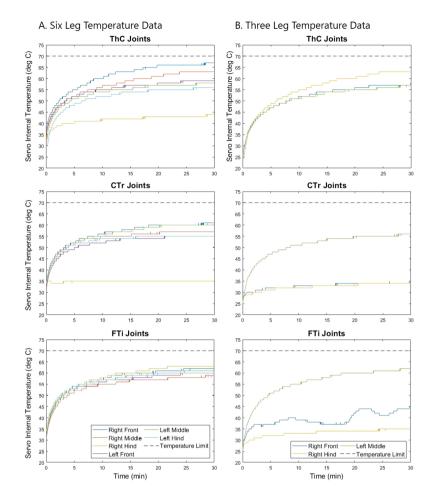


Fig. 7. Temperature data for each load bearing servo joint for a six leg stance (A) and three leg stance (B) over the course of $30\,\mathrm{min}$ or until a joint surpassed maximum operating temp of $70\,^{\circ}\mathrm{C}$.

4.2 Conclusions and Further Work

We have designed Drosophibot to mimic particular insect-like qualities and improve our previous robot, MantisBot. Drosophibot has a higher strength-to-weight ratio than MantisBot; it has the potential to distribute its weight more biologically accurately; its dynamic scale is more similar to that of its insect model; and it has compliant tarsi-like feet to better match the proportions of the animal, and reduce impact loading during walking. The next steps in Drosophibot's development will be to implement our dynamical neural control networks for walking [13,17]. We plan to specifically examine how strain-based reflexes may simplify the control of multiple legs simultaneously in stance phase, which forms a redundant manipulator. In addition, we will use Drosophibot to test our

model of the fly central complex [12], and explore how the brain may control behavior by modifying the strength of reflexes in the thoracic networks.

We will further use Drosophibot to help design experiments that can be performed in the animal. Specifically, we plan to study what kinds of information must be shared between the legs to produce coordinated walking. Behavioral rules that coordinate walking have long been known (e.g. the Cruse rules, [7]), but it is not clear whether these arise due to information transmitted between legs through the nervous system, through mechanical coupling, or both. Drosophibot, with its 18 strain gages and 18 leg joint proprioceptors, will provide us an opportunity to systematically explore how each impacts coordinated walking. Genetic tools will enable our collaborators to replicate these experiments with the animal [5], after which we can compare results to better understand how animals accomplish such robust locomotion.

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