Hummingbird-Inspired High-Speed Deceleration and Flea-Inspired Vertical Take-Off

Pavlo Vlastos [1]

Baskin School of Engineering, UC Santa Cruz

Abstract

A design for a bio-inspired robot and simulation are discussed. A flea-inspired jumping mechanism is detailed, in addition to a hummingbird-inspired wing system for accurate navigation and deceleration. The primary goal of the robot is to deliver a fragile payload, an egg, to a desired height and location. This paper reviews similar projects, research, and discusses a novel hybrid approach. The system is split into vertical take-off and controlled gliding.

Keywords: Flight, Bio-inspired, Hummingbirds, Fleas

1. Introduction

Some robots require specific infrastructure. A rumba for example requires flat surfaces to traverse, where as DARPA's Big Dog can navigate the uneven surface of a grassy hill, Boston-Dynamics (2005). Robots that do not require specific environmental geometry can be deployed in countries that have limited infrastructure to deliver important supplies, conduct search and rescue, and study hazardous environments. In the case of disaster relief, supply delivery via all-terrain, long-distance autonomous vehicles can be critical to developing nations.

This paper outlines a proposal for a high-velocity aerial robot drawing inspiration from hummingbirds and fleas. The robot will use vertical take-off, requiring no runway. Additional bio-inspiration is drawn from the manner in which humming-birds rapidly decelerate. When hummingbirds are in mating season, the males attract females executing a looping *display dive* reaching speeds of up to approximately 27 meters per second, Bennet-Clark and Lucey (1967). The system incorporates an initial acceleration mechanism to propel the robot to a high altitude. Once the apex of the trajectory is reached, hummingbird-inspired wings and tail feathers will be deployed to mimic the deceleration.

The vertical take-off mechanism is inspired from the jumping mechanism of a flea. Fleas are capable of jumping with an acceleration of 102 g-forces, (Bennet-Clark and Lucey, 1967, p. 62).

[1] *pvlastos@ucsc.edu*

This is a tremendous acceleration that is not easily reverse engineered. This proposal will explore a design for a jumping mechanism based on scaling the acceleration capable of fleas, but with a larger mass. A comparison of energy density relative to size of a payload will be made. A simple free-body diagram is outlined in **section** 2. The forward and inverse kinematics are also discussed in **section** 2.

One example of a jumping robot is a 7 gram robot capable of jumping over 1 meter in height. The approach to designing the 7 gram robot structure was largely based off of evaluating the kinetic energy required for the robot to reach a certain height. The robot was designed with the idea of carrying a payload, so a 'cost of payload' was used to further estimate the energy efficiency. An analysis of the energy stored in the spring and jumping height was conducted to see the effects of carrying a 3 gram payload and without any payload. One of the features of the design was an adjustable takeoff angle. The design was theoretically capable of jumping 108 times for a height difference of up to 148 meters, Kovac et al. (2008).

Another jumping robot was designed with an emphasis on power modulation of a series elastic actuator. To achieve power modulation in a muscle, the instantaneous power of said muscle complex must exceed the most energy that could be output by the muscle by itself. The muscle transfers energy to parallel-elastic structures and then that energy is released at energy levels that could not otherwise be realized by the muscle without the parallel-elastic structures. Essentially, this particular robot used a temporary, physical energy storage medium to amplify its jumping potential. Using this elastic structure to temporary store energy is a weight efficient method for achieving higher jump heights. Part of the inspiration for the robot design was the galago, which also exhibits power modulation, and posses the highest vertical jumping agility. The model for the design was a simple mass, spring, and damper. The spring and damper were in series and could push or pull the leg of the robot. The robot was found to be able to jump higher to 78% of the galago's jumping agility, where as previous robots were only capable of up to 55%, Haldane et al. (2016). As with the previous robot example, this galago-inspired robot was also designed with respect to a weight and jumping-energy usage relation. Its efficiency however was greater than the previous.

A third design emphasized stability over jumping height. The Gearless Omni-direction Acceleration-vectoring Topology (GOAT) used a 3-DoF design. It is capable of jumping in any direction on a plane. It uses high fidelity proprioceptive force control. While its maximum jump height is 82 centimeters, it can land on the same leg used for jumping to jump repeatedly. This contrasts with galago-inspired robot, as it was only able to jump a few times in succession. The GOAT is also capable of running-jumping trajectories, albeit mounted to a test rig. To further contrast, instead of using series-elastic actuators (SEAs), like the galago-inspired robot, the GOAT uses virtual model control. This uses motors to emulate the dynamics of series-elastic components and various other mechanical components. The use of direct-drive and quasi-direct drive actuators further assist in avoiding possible bandwidth limitations of series-elastic actuators, Kalouche (2017). The GOAT is more geared toward smaller jumps and specifically running-jumping gates of motion in any direction on a plane. Jump efficiency is not compared to something such as a galago.

A fourth example of a jumping robot is a small insect-inspired robot. It uses a small compact structure with wheel-like appendages to run, and a jumping mechanism to traverse up to 18 centimeter-tall obstacles, Lambrecht et al. (2005). The wheel-like appendages spin, but to not have a circular rim, but rather, multiple legs. This permits the robot to traverse very uneven terrain. Any obstacles that are too high for the custom wheels to overcome can be hopped over by the jumping mechanism.

Other research returns back to the galago-inspired robot. The addition of a steerable mechanism allows the series-elastic jumping leg to jump multiple times, with designed trajectories. Its mass was a mere 14 grams, with a jump height of up to 67 centimeters and a take-off angle of 75 degrees, Kova et al. (2010). A light-weight spheroid structure was used to keep the leg balanced, and to aim the jump as desired. Compared to other robot designs of this nature, this had the highest jump height per mass by an order of magnitude. It did not posses the highest jump height overall, but relative to its size, it outperforms other jumping robots. For moving small payloads over uneven terrain, this modified galago-inspired robot is one of the most advanced and efficient robots.

With regard to energy efficiency, an energy comparison between nature and synthetic designs for jumping can be made. Energy storage in passive elements is a common method for jumping insects, such as locusts, to amplify jumping power. The passive elements do not add substantial weight to the insect, but greatly improve the efficiency of the jump. In locusts, a 4 milligrams leg can store the energy of a 70 milligram muscle, Bennet-Clark (1975). Additionally, constant acceleration during the impulse, resulting from the jump can be achieved. The power rises at a steady rate from the power output of the leg. These are desirable characteristics.

The basic design of the robot outlined in this paper will be broken up in to two main sections: **1)** the initial acceleration mechanism and **2)** the deceleration mechanism. A free-body diagram will be detailed, the equations of motion and kinematics will be explained, a simulation will be made, and as a stretch-goal a prototype will be assembled.

2. Formulation of the problem

The primary goal is to deliver a payload, such as an egg to some height unharmed using a robot that is bio-inspired. The problem is broken up into two parts. The first part is to find a way to rapidly ascend updward. The second part is to implement a *reasonable* deceleration. These two subproblems use two different mechanisms, one inspired by the flea for take-off and one inspired by the hummingbird for landing.

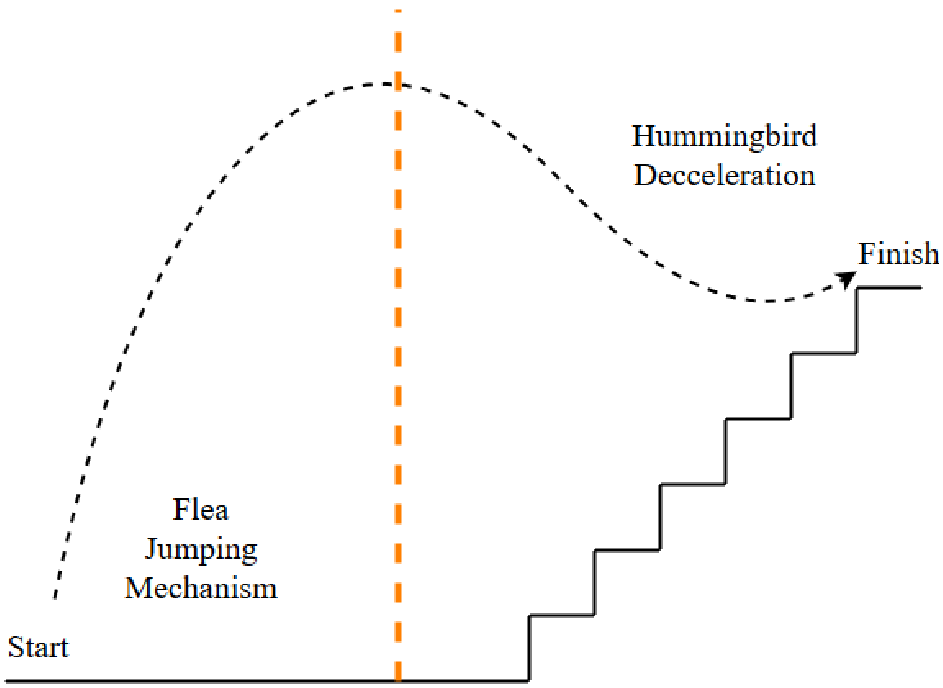


Figure 1: This is a visual representation of the goal of delivering an egg to the top of a staircase. The orange line separates the two different mechanisms into their respective roles for the trajectory of the payload.

2.1. Acceleration Mechanism

As shown in **Figure** 1, the jumping mechanism will be used to achieve substantial height for the payload delivery. In order to draw inspiration from how a flea uses its energy to jump so high, energy usage will be explored in relation to payload mass as well as maximum height. A flea can jump many times its own height, but it is small in mass, approximately 45mg (Bennet-Clark and Lucey, 1967, p. 63). Fleas have a ratio of mass to jump height and energy density. For a larger robot, a similar ratio could be achieved if energy density is proportionally higher to account for the larger mass. The larger mass is in part introduced by the need to carry an egg, which a flea does not have.

It should be noted here that there is no path planning associated with the jumping mechanism. There may be an initial jump angle relative to the ground, but guiding the egg to the desired location is dealt with in the second part of the robot design. The proposed design for the jumping mechanism is shown in **section** 4.

2.2. Deceleration Mechanism

This second part of the problem is associated with the bio-inspiration of a hummingbird. Hummingbirds are able to rapidly decelerate from specifically a diving trajectory. Assuming a substantial height is reached, this deceleration mechanism will be deployed to guide the egg to it's desired location safely. Wings will be used to realize this behavior. The design for this is shown in **section** 4.

3. Method of solution

The flea-inspired leg is the primary focus of the vertical take-off mechanism. It is treated as a two-link planar robot leg. The forward and inverse kinematics are discussed here, followed by the free-body diagram.

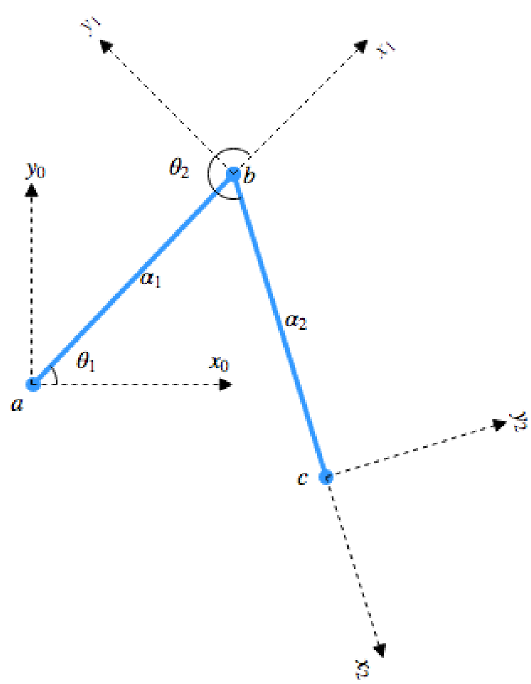


Figure 2: Model for a planar, two-link, robot leg.

Forward Kinematics:

$$x = x_2 = \alpha_1 \cos\theta_1 + \alpha \cos(\theta_1 + theta_2) \tag{1}$$
$$y = y_2 = \alpha_1 \sin\theta_1 + \alpha \sin(\theta_1 + theta_2) \tag{2}$$

The resulting **orientation matrix** is as follows:

$$\begin{bmatrix} x_2x_0 & y_2x_0 \\ x_2y_0 & y_2y_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta_1+\theta_2) & -\sin(\theta_1+\theta_2) \\ \sin(\theta_1+\theta_2) & \cos(\theta_1+\theta_2) \end{bmatrix} \tag{3}$$

Inverse Kinematics:

$$\theta_1 = \tan^{-1}\left(\frac{y_{des}}{x_{des}}\right) - \tan^{-1}\left(\frac{\alpha_1 \sin\theta_2}{\alpha_1 + \alpha_2\cos\theta_2}\right) \tag{4}$$

$$\theta_2 = \cos^{-1}\left(\frac{x_{des}^2 + y_{des}^2 - \alpha_1^2 - \alpha_2^2}{2\alpha_1\alpha_2}\right) \tag{5}$$

The inverse kinematics represents the angles, θ_1, θ_2 of the two-link leg to be functions of a desired position, (x_{des}, y_{des}). When controlling the acceleration of the robot's mass upwards, the inverse kinematics will be used to command a position of the end of the robot leg at various time steps. A desired acceleration can be incorporated into a feedback loop, which is discussed further.

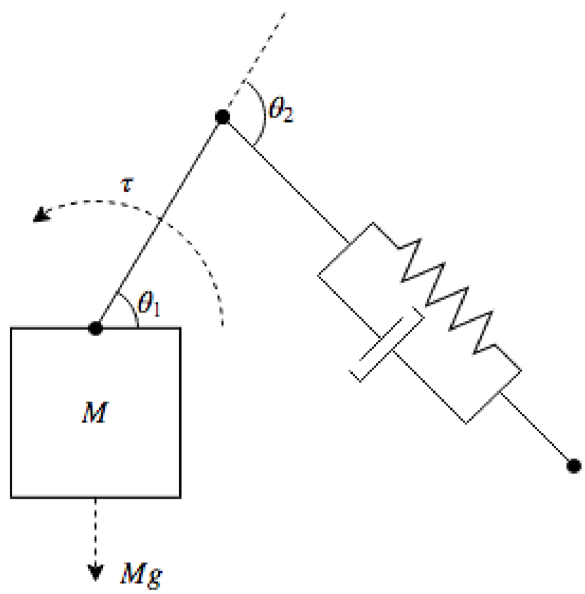


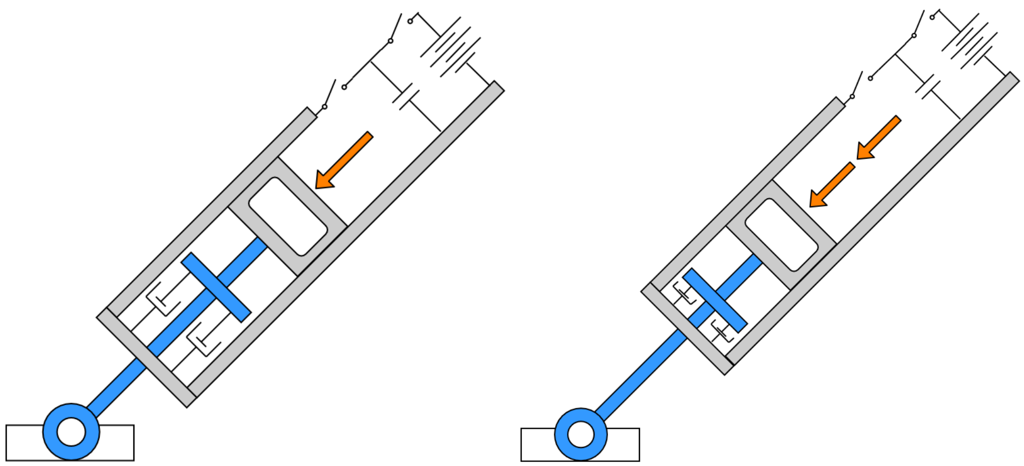
Figure 3: Free-body diagram of the FleaSlug robot

The simulation will look at a number of physical aspects of the robot, but will focus on two main things. The first is energy usage and finding a similar method to store comparable energy density in a small robot. The discharge rate of the energy used to propel the robot upward will be simulated. The second is the flight of the robot. The wing design, air resistance, and lift will be simulated.

Once the simulation is completed, a stretch goal for this project will be fabricate and construct the robot based on the simulation. A simple 8-bit microcontroller will be used to control the robot, its wings, the jumping mechanism, and possible safety features.

4. Implementation

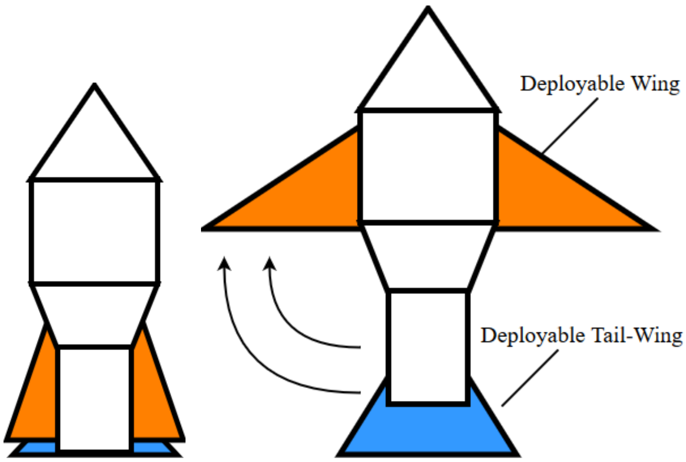
Both the jumping mechanism and wings for deceleration will be outlined here. This section shows possible designs for the robots mechanisms.



(a) Compressed jumping mechanism (b) Extended jumping mechanism

Figure 4: Example of a chart

The mechanical implementation for the flea-inspired jumping mechanism is shown in **Figure** 4. To achieve the necessary energy density, a small battery and a large capacitor will be used. The capacitor allows for large quantities of charge to be discharged rapidly. The current will flow through the armature, pushing the piston-like leg (blue) out. The micro-controller mentioned in **section** 3 will control the flow of current and capacitor charging and discharging.



(a) Folded wings (b) Extended wings

Figure 5: Example of a chart

Figure 4 shows the deployable wings. The wings must be folded at first to maximize the height. When the wings are folded air resistance is less and the jumping mechanism can propel the robot higher. The on-board micro-controller will control the timing of the wings and when the are deployed.

5. Numerical results and discussions

When numerical results are prepared, they will be shown here. The acceleration over time, the velocity over time, the position over time, and other information will be graphed and compared to the simulation if the physical robot is constructed.

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