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THE APPLICATION OF BIOINSPIRED JUMPING LOCOMOTION PRINCIPLES TO MOBILE ROBOTS – MODELING AND ANALYSIS

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ABSTRACT
Nature provides various alternative locomotion strategies which could be applied to robotic systems. One such strategy is that of jumping, which enables centimeter to millimeter-scaled insects to traverse highly unstructured environments quickly and efficiently. These insects generate the required high magnitude power through specialized structures which store and rapidly release large amounts of energy. This paper presents an investigation into the morphology of natural jumpers and derives a generalized mathematical model based on them. The model describes mathematically the relationships present in a jumping system which uses a pause-and-leap jumping strategy. The use of springs as energy storage elements for such a jumping system is assessed. The discussion is then further extended to another bioinspired approach that can be applied to a jumping robot: that of gliding using foldable wings. The developed jumping and gliding mobility paradigm is analyzed and its feasibility for mobile robot applications is discussed.

INTRODUCTION
Robots are presently being developed for many tasks in rugged environments, including search and rescue, exploration, surveillance, and mobile sensor network setup. This requires the development of robotic systems that possess versatile locomotion mechanisms in order to traverse rough and unstructured environments.

Typically this is achieved through the use of wheels, tracks, or legs. However there are limitations to the abilities that these locomotion mechanisms possess. For instance the obstacle traversing ability of a wheeled robot is restricted to 1.5 times the wheels' diameter [1]. Tracked robots are commonly deployed in rugged terrain operations, but to surpass obstacles they require extensions to the chassis like articulated fins [2] or hybridized structures [3]. Still, the height of the obstacle that they can overcome is limited. Similarly the predominantly experimental legged robots face problems in unstructured environments, with prototypes either limited to smoother terrains [4], or moving too slowly to be viable solutions [5]. There is also unresolved control complexities associated with the stability of legged robots, although designs like the Big Dog [6] and the rHex [7] are promising legged prototypes for rough terrain travel.

The need for alternative locomotion strategies has led many researchers to look to nature for inspiration. Various innovative designs have been based on concepts found in nature. One such concept is that of jumping, which is used by many animals and insects as a mechanism for rapid locomotion. We will focus on insects that jump, since they most effectively utilize jumping to compensate for their small size while negotiating highly unstructured terrain.

Some notable high jumping insects are the locust, grasshopper, flea, and froghopper. These creatures are able to achieve remarkable jumping performance through the development of specialized hind legs and energy storage elements. The hind legs in most jumping insects are longer to provide extra leverage and extended acceleration duration [8]. In addition, these insects have developed energy store-and-release mechanisms, which, though different in morphology, serve the same purpose. These will be discussed in more detail in the following section.

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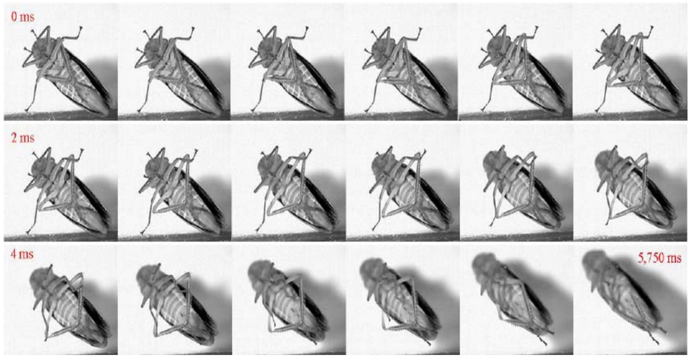

FIGURE 1: THE MOTION OF THE HIND LEGS DURING JUMPING FOR A FROGHOPPER [13]

Much research has been performed on jumping insect kinematics [9-11]. Models and robots have been built that employ the same principles. For example, Kovac et al. [12] built a 7 gram robot based on the performance of the grasshopper which is able to achieve jumps of up to 27 times its body height. The "Grillo" robot, based loosely on the principles of the froghopper, can move with a forward velocity of 1.5 ms^{-1}[13].

In this paper we will highlight some of the key issues that influence jumping performance. To this end, we will first develop a generalized mathematical model based on a self-energizing ballistic jumper. The model developed will be generic in the sense that it can be applied to many jumping systems, but it will be fundamentally based on legged jumping morphology. We will then introduce non-dimensional parameters which can be used to study key relationships in the model to establish important design considerations. Further, since the primary purpose of this study is as a step towards designing robotic systems based on nature, we will analyze the applicability of two different energy storage mechanisms on jumping performance. Finally, we will discuss a specialized case also based on nature: gliding, as is used by bats and birds, as an extension of ballistic jumping. The benefits, drawbacks, and feasibility of the combined jumping gliding mobility paradigm will be discussed.

JUMPING LOCOMOTION IN NATURE

As a precursor for model development, we first studied various jumping methodologies as they are employed in nature. Most of the natural jumping mechanisms vary with respect to the specific nature with which the thrust force is imparted to the ground, but the basic principle is the same: energy is slowly stored in specialized structures and then rapidly released to provide the required acceleration. Some insects achieve this through abdominal movement, like the springtail [14], while others, like the stick insect, combine forward motion of the abdomen with movement of the legs [15].

Of interest is the group of insects that propel themselves using a simultaneous movement of their specialized hind legs. This motion lends itself well to kinematic analysis as well as mechanical replication. The mechanism of propulsion and the specific muscle or structure where energy is stored may differ. For example, fleas use the trochanteral depressor muscles [16], while locusts and bush crickets use tibia extensor muscles [17]. Usually the hind legs are elongated in jumping insects, providing a longer moment arm and extended acceleration times to increase jumping performance. This can be observed in Bush crickets, which use direct muscle contractions to power very long legs. In comparison, fleas use a catapult mechanism in which a slow contraction of the muscles provides energy, which is stored in the skeleton and then suddenly released, providing a very high power output [16]. Locusts use a combination of energy storage and specialized long hind legs to power the jump [17].

Finally, froghoppers, which are a recently discovered class of insects, use a mechanism akin to a crossbow to shoot their hind legs into the ground [18], as shown in Figure 1. They are able to achieve accelerations of up to 5400 ms^{-2}, reaching heights of 700mm [8], making them the best jumpers in nature. The hind legs in this case are roughly half the length of the body, significantly shorter than other insects like the grasshopper and locust. Additionally, the mass of the hind legs in the froghopper is 2% of the body mass, an extremely low quantity as compared to other jumping insects. The importance of this will be discussed in the coming sections.

Key Principles

Much research has been performed on the jumping performance of grasshoppers, froghoppers, fleas, and locusts for robotic design [12, 13, 19, 20]. The requirements for successful self-propelled jumping locomotion can be summarized as:

a) A reduction in the mass of the hind legs versus the body
b) Increase in the energy storage capacity of the elastic element
c) Reduction in friction and drag forces
d) Symmetrical design and synchronized hind leg movement

In nature, (a) can readily be observed. The previously described insects have hind legs which are a fraction of the mass of the rest of the body. (b) is the result of the specialized mechanism which allows energy storage, so that the power output is increased significantly. Series-elastic actuators use the same principle of using an artificial muscle with a motor, although to a lesser degree of energy storage [21]. Air friction and drag forces are reduced by selecting a body shape which has minimal cross-sectional area with respect to the direction of travel. If the design is symmetrical and the hind legs motion is synchronous the system exhibits a controlled force profile on the ground, allowing a more stable jump to be performed.

MATHEMATICAL JUMPING MODEL

High jumping insects perform a jump through two general steps, which are:

(i) Slow charging of the energy storage mechanism. This could be through a compression of the thigh muscles for mammals, or the combined effects of flexion and extension to charge the semi-lunar process as in locusts [22]

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(ii) Energy release. This is usually performed at a highly accelerated rate and provides the necessary kinetic energy to lift the body off the ground.

Many different design embodiments can be realized with respect to the method of energy release, the mechanism by which the released energy is transferred to the ground, and the number of active degrees of freedom in the leg. Each of these enhances the accuracy of the derived model, but also increases its complexity. However the jumping model is designed, the basic principle of slow-charging and quick releasing of an energy storage mechanism remains consistent. In previous works, Alexander [23] presented a two-legged model which he used to analyze the jumping performance and characteristics of various animals and insects. A simple two-mass model has been presented in [24, 25] as well.

The model presented here is based loosely on the jumping principles exhibited by the froghopper's hind legs, as shown in Figure 1. The legs are connected at the hip and foot by frictionless pin joints, effectively creating a four-bar mechanism. This will allow the analysis to be extended to cases involving mechanical energy storage elements such as springs. Since we are concerned only with developing relationships between jumping performance parameters, we use a two-dimensional model and consider vertical jumping. The model can readily be expanded to a three dimensional case by introducing an orientation angle, but for the purposes of our analysis, a 2-D model suffices.

Figure 2 shows three stages of jumping prior to takeoff from the ground. The terms in Figure 2 are as follows:

- g is gravity (ms^{-2})
- F_{act} is the force of actuation (N), which is a conceptual force that is converted to stored energy. In a biological system, this would be force applied by the muscles, while in an artificial system this would be the torque provided by the motor over the moment arm to charge the spring.
- m_b, m_l and M are the masses (kg) of the body, the legs, and the total mass respectively. In our model, the mass of the legs and the foot are considered as one, as described by [24].
- F_{max} is the maximum force exerted to provide maximum energy to the elastic element.
- F_{jump} is the thrust force that the actuator produces to power the jump, propelling the jumper vertically at an initial velocity v_{jump}.
- l (m) is the length of each of the links of the mechanism
- y_1 and y_2 (m) correspond to the minimum and maximum heights of the center of mass of the body, which is assumed to lie within the same horizontal line as the hip joint [8].
- y_{ext}, or l_{ext}, is the distance that the center of mass accelerates, from the initial release of the stored energy up until the foot is about to leave the ground, and is given as:

$$y_{ext} = 2l\left[\sin\left(\frac{\theta_2}{2}\right) - \sin\left(\frac{\theta_1}{2}\right)\right] \quad (1)$$

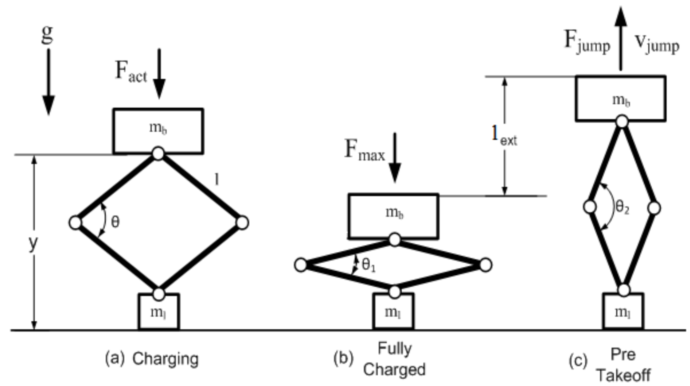

FIGURE 2: THREE STAGES OF THE JUMPING ROBOT MODEL

Using a non-dimensional system analysis technique, as previously proposed in [24] and [26], the system can be described as follows:

$$f\,(m_b, m_l, m_{act}, l_{ext}, h_{\max}, F, g) \quad (2)$$

Each of these seven variables is a function of at most three basic parameters, which are mass [M], length [L], and time [T].

According to the Buckingham-Π Theorem [27], there exist four non-dimensional variables which describe the system. These can be found by setting

$$m_b^{\,l}, m_l^{\,m}, M^n, l_{ext}^{\,o} h_{\max}^{\,p}, F^q, g^r = non-dimensional \quad (3)$$

Through an analytical approach [24, 26], the relationships between the parameters described above can be evaluated, resulting in the following non-dimensional parameters:

$$\left(\frac{m_b}{M}\right)^l \left(\frac{m_l}{M}\right)^m \left(\frac{h_{\max}}{l_{ext}}\right)^p \left(\frac{F}{Mg}\right)^q \quad (4)$$

Where M is the total mass of the system. We select the following parameters to describe the system, as previously discussed in [24]:

$$\hat{H} = \frac{h_{\max}}{l_{ext}} \quad (5)$$

$$\hat{M} = \frac{m_b}{m_l} \quad (6)$$

$$\hat{F} = \frac{F_{jump}}{Mg} \quad (7)$$

These are dimensionless yet physically meaningful parameters for system evaluation. $\hat{H}$ gives a ratio between the

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maximum height the robot can jump versus the leg extension, therefore one design criteria is to maximize $\hat{H}$. $\hat{M}$ relates the body mass to the leg mass, and directly influences the efficiency of the system. $\hat{F}$ is the force provided for the jump versus the weight of the robot.

In order to find relationships between these parameters, we perform an energy study on the system. Air resistance effects are modeled as a loss of maximum height, such that $h_{max}=\alpha h_{ideal}$, where $0<\alpha<1$. Then,

$$gh_{\max} = \frac{1}{2} v_{jump}^{2} \tag{8}$$

Similarly, considering the system in the pre-launch stage, (Fig 2 c.), the following equation can be readily obtained:

$$F_{jump} - m_b g = \frac{m_b v_{acc}^{2}}{2 y_{ext}} \tag{9}$$

Here, v_{jump} is the velocity of the system after loss of ground contact, while v_{acc} is the instantaneous velocity of the upper mass immediately before loss of ground contact. Conservation of momentum results in the following equation:

$$m_b v_{acc} = (m_b + m_l) v_{jump} \tag{10}$$

This results in:

$$v_{jump} = \eta v_{acc} \tag{11}$$

$$\eta = \frac{\hat{M}}{\hat{M} + 1} \tag{12}$$

η is a conversion efficiency factor [25] that is dependent on the variation in mass between the body and the leg. It is an important design consideration to have this factor as close to unity as possible by constructing the legs as a fraction of the mass of the body, so that energy losses are minimized. As previously stated, this principle is readily observed in nature.

Equations (9), (11), and (12) combine to give:

$$v_{acc} = \sqrt{\frac{2 y_{ext} (F_{jump} (\hat{M} + 1) - M\hat{M}g)}{M\hat{M}}} \tag{13}$$

Through an energy balance on the system, where friction due to drag has been modeled as a reduction in the maximum height, (13) can be combined with (8) to give a relationship between the normalized height, the thrust forces, and the mass, as [25]:

$$\hat{H} = \frac{(F_{jump} - Mg)\hat{M}^{2} + F_{jump}\hat{M}}{Mg(\hat{M} + 1)^{2}} \tag{14}$$

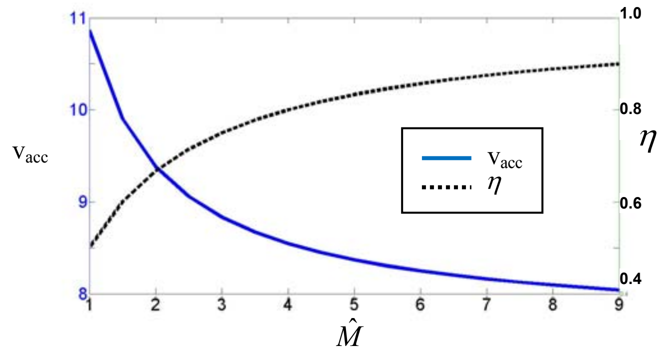

FIGURE 3: THE EFFECT OF $\hat{M}$ ON η AND v_{acc}

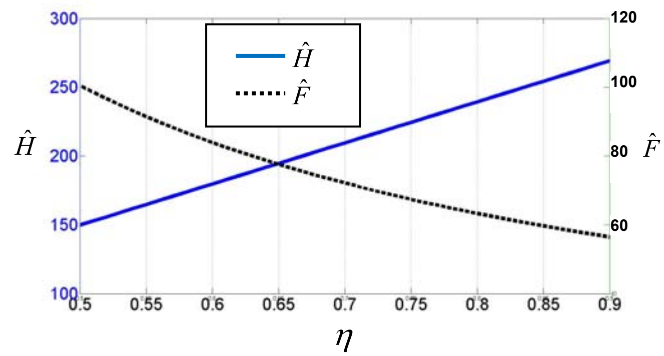

FIGURE 4: THE EFFECT OF η ON $\hat{H}$ AND v_{acc}

Combining (14) and the dimensionless parameter given in (7), we get a non-dimensional equation given by:

$$\hat{F} = \frac{\hat{H} + \eta^{2}}{\eta} \tag{15}$$

Where η was previously defined in (12). This equation describes the force at takeoff, normalized over the body weight, versus the relative jump height and the mass distribution in the jumper.

Equation (15) provides an important relationship between previously defined normalized parameters. This equation, combined with (14), gives a means to analytically determine the relationships between the parameters involved in jumping. The non-dimensional nature of the formulation ensures its applicability to any jumping system.

For the purposes of analysis, we select the parameters as $\hat{F} = 200$, and the jump height $\hat{H} = 50$. Then through the application of the derived equations, graphical relations can be generated using numerical analysis software, which are shown in Figure 3 and Figure 4. It can be seen that for a fixed mass and takeoff force, the velocity to which the upper mass accelerates decreases exponentially as the fraction $\hat{M}$ increases. η follows an opposite trend, showing an increase as $\hat{M}$ increases. Similarly,

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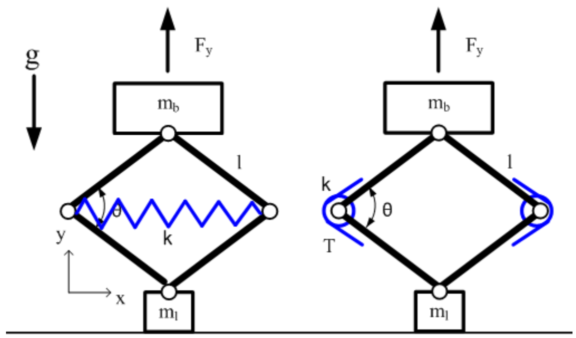

FIGURE 5: ENERGY STORAGE DESIGNS USING SPRINGS

it can be seen in Figure 3 that as η varies from 0.5 to 0.9, $\hat{H}$ increases linearly for constant system energy. The $\hat{F}$ required to cause the jump decreases for increasing η, which shows the importance of keeping η as large as possible.

Case Study

Since the primary purpose of this study was as a step towards design of a robotic jumping system based on biological principles, the jumping model was analyzed under two specific mechanical energy storage cases: linear and torsion springs applied to the knee joint. Springs are a robust, light weight, and effective means of energy storage. They are especially suited to the slow-charging and rapid release of energy, which is a requirement for effective jumping. They are a consistently used energy storage mechanism for jumping machines [12, 13].

The analysis considers the springs to be fully charged to energy E_0, followed by the subsequent discharging phase which is developed for two cases, as shown in Figure 2.

Linear Spring. Figure 5(a) shows the developed four-bar mechanism with a linear spring attached through the knee joints. A similar mechanism has been described previously to model frog jump kinematics [28]. In this case, the force F_y developed by the spring can be derived using the principle of virtual work [1]:

$$F_x dx = F_y dy \tag{16}$$

$$F_x = -k(x - l_0) \tag{17}$$

Where l_0 is the length of the spring at rest. For our case,

$$y = 2\sqrt{l^2 - \left(\frac{x}{2}\right)^2} \tag{18}$$

$$x = 2\sqrt{l^2 - \left(\frac{y^2}{2}\right)} \tag{19}$$

Rearranging (16) and evaluating,

$$F_y = \frac{ky\sqrt{l^2 - \left(y^2/2\right)} - l_0}{\sqrt{l^2 - \left(y^2/2\right)}} \tag{20}$$

This can be written in terms of the angle θ as:

$$F_y = \frac{kl\sin\left(\frac{\theta}{2}\right)\sqrt{l^2 - l^2\sin^2\left(\frac{\theta}{2}\right)} - l\cos\left(\frac{\theta}{2}\right)}{\sqrt{l^2 - l^2\sin^2\left(\frac{\theta}{2}\right)}} \tag{21}$$

Where k is obtained by

$$E_0 = \frac{1}{2}k(l_{max}{}^2 - l_0{}^2) \tag{22}$$

Torsion Spring. In this case, helical torsion springs of stiffness k are wound around the knee joints. According to the principle of virtual work:

$$Td\theta = F_y dy \tag{23}$$

Where the torque T provided by the spring is given as:

$$T = k\theta \tag{24}$$

From the law of cosines, the height of the upper joint is given as:

$$y = l\sqrt{2(1-\cos\theta}} \tag{25}$$

Then F_y is obtained by solving (23) using (25), resulting in:

$$F_y = \frac{k\theta\sqrt{2(1-\cos\theta}}{l\sin\theta} \tag{26}$$

The spring constant k can be calculated using the initial energy of the system, E_0, such that

$$E_0 = \frac{1}{2}k(\theta_2^2 - \theta_1^2) \tag{27}$$

Where E_0 is determined through the required jumping height. As a simple study to show the characteristics of the force profiles for both linear and torsion spring, we assumed the system mass and dimensions based on those of a locust [22] as: m=0.0015kg, h=0.5m, l=0.01m. Then, E_0 is 7.4mJ. Assuming the mechanism has a maximum and minimum angle of θ_2 = 150 deg and θ_1 = 15 deg, then equations (21) and (26) give the variation of the force profile with changing angle. This is shown in Figure 6.

It can be seen that the linear spring in this arrangement has a nonlinear force profile, peaking once before dropping. It has been argued that this is a desirable characteristic as it reduces the risk of premature takeoff [1]. In contrast, the torsion spring exhibits a continuously increasing thrust force which has a greater magnitude that the linear spring.

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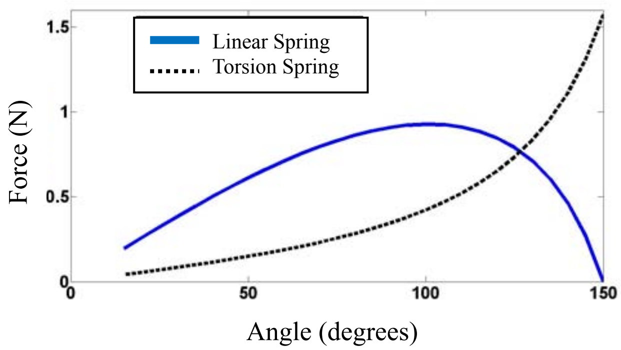

FIGURE 6: FORCE PROFILE VERSUS ANGLE FOR TWO SPRING CONFIGURATIONS

In terms of effectiveness given the same amount of initial energy, the torsion spring provides a higher thrust force on the ground. However, the magnitude of the force increases towards the end of the unloading cycle for the torsion spring, at which time the foot may have already lost contact with the ground, resulting in substantial energy losses.

In an ideal case, the torsion spring performs better than the linear spring for this mechanism, although the issue of premature takeoff from the ground needs to be further investigated for both types of spring. Ground takeoff occurs when the upward force provided by the spring completely counteracts the mass of the system, and for optimum design it is essential that acceleration duration is maximized. This can be achieved through material and spring selection that ensures ground takeoff occurs towards the end of the spring unloading cycle.

JUMPING AND GLIDING MOTION

This section provides an analysis for a new method of locomotion – jumping followed by gliding motion. In theory, this can be achieved by employing foldable wings to a jumping robot. The wings will remain folded during the initial phase of the jump, so that it can be modeled as an unpowered projectile. Once it reaches an optimum height and velocity, it will launch the gliding mechanism to take advantage of the introduced lift forces and perform unpowered steady state gliding flight [29].

The theoretical benefits of such a motion are to increase the horizontal distance traveled, increase in-flight control of the trajectory of the robot, and decrease potentially catastrophic impact forces upon landing. Figure 7 shows a conceptual rigid body ballistic trajectory.

The terms in the figure are defined as follows:

- v_0 : takeoff velocity (ms^{-1})
- α_0 : initial takeoff angle (degrees)
- y_{max} : the maximum height attained by the projectile, dependent on the ballistic flight trajectory (m)
- x_g, y_g, t_g : the respective distance and time at which the gliding mechanism will be released (m, s)
- x_{max}: the maximum range covered by the given system.

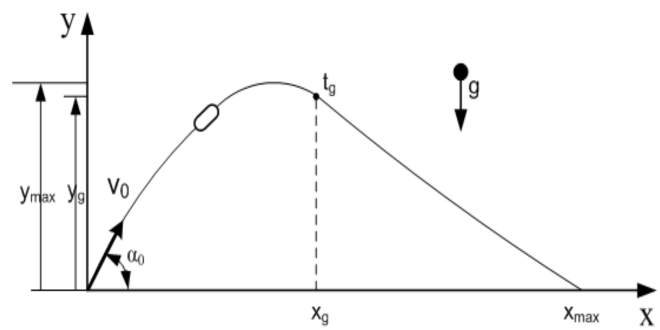

FIGURE 7: JUMPING-GLIDING MOTION SCHEMATIC

Taking into account drag and lift forces as they apply to any rigid body following a ballistic trajectory, we can derive the following governing equations:

$$m\ddot{x} = -f_d \cos(\alpha(t)) - f_l \sin(\alpha(t)) \tag{28}$$

$$m\ddot{y} = -f_d \sin(\alpha(t)) - f_l \cos(\alpha(t)) - mg \tag{29}$$

The drag force f_d and the lift force f_l are given as:

$$f_d = Dv^2 = D(\dot{x}(t)^2 + \dot{y}(t)^2) \tag{30}$$

$$f_l = Lv^2 = L(\dot{x}(t)^2 + \dot{y}(t)^2) \tag{31}$$

Where,

$$D = \frac{1}{2}\rho A_d c_d \tag{32}$$

$$L_f = \frac{1}{2}\rho A_l c_l \tag{33}$$

This gives the horizontal and vertical acceleration in terms of the drag, lift and inertial forces. A constraint on lateral motion imposes the relation:

$$\alpha(t) = \arctan\left(\frac{\dot{y}(t)}{\dot{x}(t)}\right) \tag{34}$$

The terms above are defined as follows:

- ρ = air density,
- A_d = Drag area, normally considered as the area perpendicular to the direction of travel,
- c_d = Drag coefficient,
- A_l = Lift area, taken as the wingspan
- c_l = Lift coefficent.

For simple flow conditions and geometries and low inclinations, the coefficient of lift can be approximated using the following equation [30]:

$$c_l = 2\pi\theta \tag{35}$$

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where θ is the angle of attack expressed in radians. The coefficient of drag depends on parameters such as the Reynold's number, shape of the object, and air conditions [31]. Unpowered gliding motion for small UAV's is modeled as low Reynold's number flight [32].

To model the deployable wing, we note that the wing folding mechanism will be released instantaneously. For this reason, the lift force has the following constraint:

$$\begin{aligned} L &= 0, t < t_l \\ L &= L_f, t \geq t_l \end{aligned} \tag{36}$$

If the friction forces on the model are simplified to include a cost function c_f which acts as a reduction factor on the total energy, then the energy available on the system will be c_f multiplied by E. Then the maximum height that the body reaches, h_{max}, is given as:

$$h_{\max} = c_f E \sin(\alpha_0)^2 \tag{37}$$

Similarly, the velocity at this maximum height is horizontal, and is given by:

$$v_{top} = \sqrt{\frac{2c_f E}{m_{jg}}} . \cos(\alpha_0) \tag{38}$$

We consider a simple case of a small jumping machine that weighs 10 grams, versus a jumping and gliding machine that weighs 15 grams. The energy released for the jump is assumed to be enough to raise both masses to the same height, with an assumed takeoff value of $6 ms^{-1}$. This is in close comparison to the best performing jumping robot created to date [12]. Assume that the gliding mechanism is launched at the highest point of the trajectory, and that the area of the wingspan is 40x the longitudinal area of the glider. The launch angle is 75 degrees. Through an iterative numerical procedure, we find the variation in horizontal distance traveled for the ballistic jump versus the glide. This is shown graphically in figure 8. For this case the increase in distance traveled is 0.14m, resulting in a total increase in horizontal distance traveled of 14.5%.

Future work in this regard will be in determining the cost of jumping and gliding with respect to initial energy available to the system, given the increase in mass. Further, we will analyze the size of the wingspan which can be designed given the mass and stored energy constraints. We will attempt to find various tradeoff parameters which will enable the systematic creation of a hopping-gliding system. This is a challenging problem because of the nonlinearity involved in the governing equations of ballistic jumping under the influence of drag and lift. Our final aim is to use aerodynamic principles to design a system which when launched will be able to autonomously deploy its foldable wings and perform steady state controlled gliding flight to the ground.

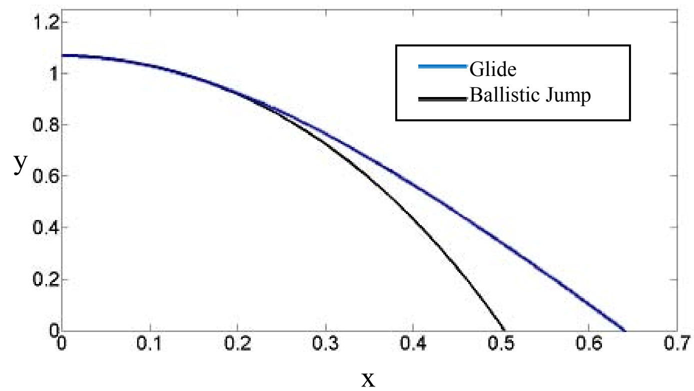

FIGURE 8: TRAJECTORY WITH AND WITHOUT WING LAUNCH

CONCLUSIONS AND FUTURE WORK

In this paper we presented an analysis of jumping motion using a non-dimensional analytical approach. We derived a legged jumping model based on froghopper jumping morphology. Important relationships between different parameters of the system and the effects they have on the jumping performance were highlighted. Additionally, the use of two different types of mechanical energy storage elements was discussed and their effectiveness analyzed. This paper presented some useful insights into the energetic of jumping locomotion. We then furthered our discussion to another bioinspired locomotion approach – ballistic jumping followed by flexible wing gliding. We found for a simple case that an increase in horizontal distance traveled of 14.5% was possible through the application of a gliding mechanism, assuming the energy costs associated with the extra weight are met. Our future work involves refining the model so that it is a more realistic depiction of jumping motion, which will allow the evaluation of different leg mechanisms. Effects of premature ground takeoff, system vibrations, and friction in the joints and the air will be incorporated into the analysis. We ultimately aim to develop a physical prototype which is capable of high powered jumping followed by ballistic gliding motion.

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