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BIOINSPIRED JUMPING MOBILITY CONCEPTS FOR ROUGH TERRAIN MOBILE ROBOTS

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ABSTRACT
Mobile robots face great challenges in terms of mobility when traversing rough terrain, especially obstacle filled environments. Current terrestrial locomotion mechanisms such as wheels, tracks, and legs, face difficulties surmounting obstacles equal to or greater than their own height. This is especially true for smaller robots. In this respect, bioinspired approaches offer some solutions. Some insects in particular tackle rough terrain locomotion by performing high powered jumps. Their morphology has evolved to create specialized energy storage structures, and their hind legs have adapted to provide improved mechanical leverage. This paper investigates jumping as employed by insects and develops principles pertinent for the design of a jumping robotic system. A mathematical model depicting bipedal jumping is presented. The model includes mechanical energy storage elements in the form of springs for the purpose of assessing jumping locomotion for robotic applications. This model will assist in analyzing jumping locomotion and presenting some insights, as well as rough dimensioning of system parameters to achieve desired jumping performance.

INTRODUCTION
Mobile robot systems are adapting to take on various challenges outside of controlled laboratory settings. This necessitates the development of locomotion strategies, which will allow mobile robots to travel over unstructured topographic conditions. Current locomotion technology focuses on conventional wheeled or tracked systems. For rough terrain applications, tracks are favored due to increased traction provided by their design. The Packbot [1] is an example of a popular tracked vehicle employed in military applications.

These conventional terrestrial locomotion methods have shortcomings when employed for rough terrain travel, particularly for obstacle negotiation. Wheeled vehicles excel at smooth terrain, but their rough terrain performance is limited unless design modifications are made to the chassis like additional articulated joints [2]. Tracked vehicles are capable of handling rougher conditions, but they too face problems when dealing with obstacles of the same order of magnitude as the robot size, unless design modifications are made to the structure like articulated fins or hybridized structures [3, 4]. The third major alternative involves legged locomotion, but it is still predominantly experimental at this stage, and requires complex control and heavy actuation, which makes it unfeasible for field operations.

Certain tasks like reconnaissance, scouting, sensor network setup, or planetary exploration, whether on Earth or other planets, require a fast, efficient, and robust locomotion strategy to deal with varying and often unknown conditions. The most effective way to travel over rough terrain would be through an aerial approach. There are energetic costs associated with this method, which limit the applicability and mission duration of micro air vehicles; for example, the four-rotor MAV presented in [5] has a flying duration of 30 minutes without payload. Micro air vehicles are also encumbered when traveling in enclosed surroundings, as can be found in cave exploration or disaster sites.

Nature provides us with many insights into locomotion strategies when traversing rough terrain. Creatures are able to travel in many different ways, such as crawling, walking, slithering, flying, and swimming, depending on their individual morphology and the terrain they travel in. The manner of locomotion is related to the scale and weight of the creature [6]. Animals change their gait strategy, posture, and effective mechanical advantage as their size changes in order to minimize induced stresses and maintain motion efficiency [7]. Additionally, for very small creatures, the grain size hypothesis [8], which states that the relative size of obstacles increases at smaller scales, has led to the evolution of these millimeter and centimeter scaled insects and animals to adopt alternative locomotion techniques.

One very effective method developed, particularly in smaller insects to move across rough terrain, is jumping. These insects use high powered jumps to overcome obstacles in a pause-and-leap strategy [9, 10]. For this purpose, the insect morphology has evolved, resulting in the development of specialized structures for energy storage and rapid release [11]. The hind legs are also adapted to provide increased mechanical leverage for jump thrust [12]. This is advantageous because a small insect can travel forward by launching itself off the ground, regardless of the type of terrain, and maintain locomotion efficiency.

This paper investigates the jumping locomotion method as employed by insects and its applicability to small scale mobile robotic systems. First, ballistic jumping motion is presented in order to highlight necessary design considerations and the effect of scaling on jump performance. The jumping technique used by insects is analyzed and presented, and a mathematical model is derived based on jumping insect morphology, but modified to take into account mechanical design considerations. The model provides an analytical tool for the optimum design of a jumping mechanism by identifying key relationships and considerations. Issues of energy storage and release using conventional electromechanical components are also discussed.

JUMPING PRELIMINARIES

Jumping as employed in nature follows a ballistic trajectory upon release [13]. The initial energy is either stored or exerted directly by the muscles to provide a thrust force against the ground, which is used to overcome the weight and propel the body. Once ground contact is lost, there are no propulsive forces applied to the body and the resulting motion can be described using simple ballistic equations.

Through energy conservation principle, the kinetic energy of the body at takeoff equals the potential energy at the maximum jump height y_{max}, assuming there are no air friction losses or foot slippage effects on the ground. This results in:

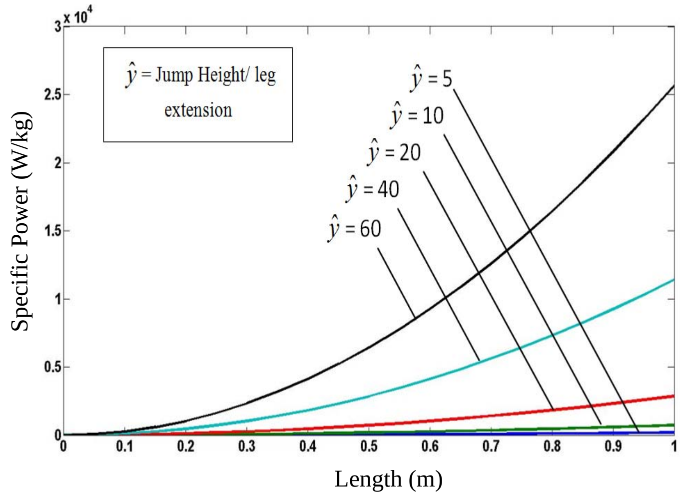

Figure 1: Variation in Specific Power Versus Leg Length for Different Jump Heights

$$y_{\max} = \frac{(v\sin\theta)^2}{2g} \tag{1}$$

where g is the gravitational acceleration, v is the takeoff velocity, and θ is the orientation angle at takeoff. Similarly, the range of motion of the jumper is given by:

$$x_{\max} = \frac{\left(v^2\sin 2\theta\right)}{g} \tag{2}$$

These elementary equations describe the motion of a ballistic jumper in ideal conditions. The effects of drag reduce the maximum height and range of insects that employ jumping by a great degree, in particular smaller insects; the flea jumps at an energy conversion efficiency of 63%, while the larger locust jumps at an efficiency of 92% [14]. It has been reported in [7] that as the scale approaches 10^{-2}m, the adverse effects of drag on jumping performance diminish, particularly for a dense body such as a robot.

For a system jumping from rest, the power required to perform a jump is given by the equation:

$$P = \frac{mv^3}{2l} \tag{3}$$

where m is mass, v is takeoff velocity, and l is the acceleration distance. Another relation between power, mass, and acceleration can be readily obtained as [15]:

$$y_{\max} = \left(\frac{2lP}{m}\right)^{\frac{2}{3}} \times \frac{1}{2g} \tag{4}$$

Figure 1 shows the increase in the specific power (P/m) as the characteristic length of the system increases for different jumping heights. The specific power requirement to achieve

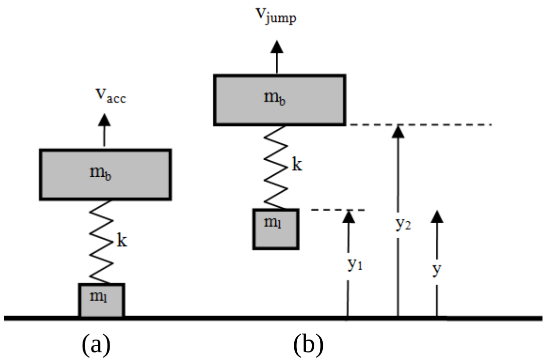

Figure 2: Schematic of a Two-Mass Spring-Loaded Jumping System: (a) before, and (b) after loss of ground contact

high jumps increases significantly as the characteristic length of the system increases, particularly for higher jumps. At smaller scales, the required specific power does not vary significantly for different jump heights, making it more beneficial to design miniaturized jumping systems.

Additionally, it is well understood that body forces, like weight, are proportional to l^3, which means that a larger body undergoes much higher forces and stresses if their performance is compared to smaller animals. This is impossible in practice due to the maximum yield stress of the bone and muscle. As a consequence, it is more feasible, both in nature and in manmade design, for miniature systems to undergo high forces like the ones encountered during jumping [7].

It can be seen from equations (3) and (4) that as the acceleration length l is reduced, the power output must be increased to compensate. As a consequence, it becomes necessary for small sized jumpers to incorporate an energy storage element to work in series with the actuation, since direct actuation at that scale will not provide enough power. These concepts will be explored further in the following sections.

A Simplified Jumping Model

The distribution of mass in a legged jumper has a direct impact on the jumping performance [16]. This principle is readily observed in nature, for instance the mass of the hind legs is 2% of the body mass in the froghopper, one of the best performing insects [11], and 3.8% in the leafhopper [17]. This principle is illustrated in Figure 2, which shows a simplified two-mass spring powered jumping system. The body has a mass m_b, and the legs are modeled as a mass m_l connected to the body through a massless linear spring.

The model described in Fig. 2(a) is immediately prior to takeoff from the ground, where the spring is at full extension and the top portion of the system has a velocity of v_{acc}. The foot is stationary at this instant. Fig 2(b) shows the system immediately after ground contact has been lost, with an instantaneous velocity of v_{jump}.

The momentum of the system must be conserved at stages (a) and (b). This leads to the following relation:

$$v_{jump} = \eta v_{acc} \tag{5}$$

where

$$\eta = m_b / (m_b + m_l) \tag{6}$$

is a conversion efficiency factor relating the body mass to the total mass [18]. Minimization of this factor, or reducing the proportion of the leg mass with respect to the body mass, has a direct effect on increasing the takeoff velocity. It becomes a necessary design consideration for a jumping robot to create a legged mechanism which is light weight yet capable of withstanding the enormous stresses associated with jumping.

JUMPING IN NATURE

In this section, we explore natural jumping systems. In particular our focus is on insect jumpers, since their jumping performance is superior to mammals or amphibians both in terms of specific power output and relative jump height. [19]. Insects use a pause-and-leap jumping strategy, in which a jump is followed by a period of inactivity during which preparations are made for the next jump.

There are differing techniques employed by insects for the manner of energy storage and release, as well as the leg structure responsible for imparting the energy to the ground. For example, fleas use the trochanteral depressor muscles [20], while locusts and bush crickets use tibia extensor muscles [21]. Usually the hind legs are elongated for 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 [20]. Locusts use a combination of energy storage and specialized long hind legs to power the jump [21].

Evolution has caused morphological variations, but the strategy employed is the same: the insect will ‘charge’ its energy storage element by performing muscular work. This energy will then be released over a very short period of time, to the order of milliseconds, to provide the required thrust force to lift the insect off the ground.

Usually jumps performed in this manner are haphazard, with the insects falling in random orientations, from which they upright themselves and prepare for the next jump [22]. Applying similar principles to a robotic system will require addressing jump stability issues and synchrony between the two hind legs.

TABLE 1: A COMPARISON OF INSECTS THAT EMPLOY THE PAUSE-AND-LEAP JUMPING TECHNIQUE

	Mass (mg)	Hind Leg Extension (mm)	Maximum Jump Height (mm)	Jump Height/Leg Extension	Takeoff time (msec)	Takeoff velocity (ms^{-1})	Mechanism of energy storage
Froghopper [11]	**12.8**	**2.1**	**700**	**333.33**	**0.875 – 1.5**	**2.5 – 4.7**	**Bending of the Pleural Arch**
Rabbit Flea [20]	0.45	0.5	49-62	124	0.75 – 1	0.8 – 1.3	Resilin Pads
Locust [21]	1,440-1860	61.26	546	8.913	25– 30	2.5 – 3.2	Semi-Lunar Process
Cricket [24]	600	36.5	200	5.48	21-32.6	1-2.12	None (direct muscular contraction)
Leafhopper [17]	18.4	6.0	156	26	2.75	2.9	Bending of the Pleural Arch

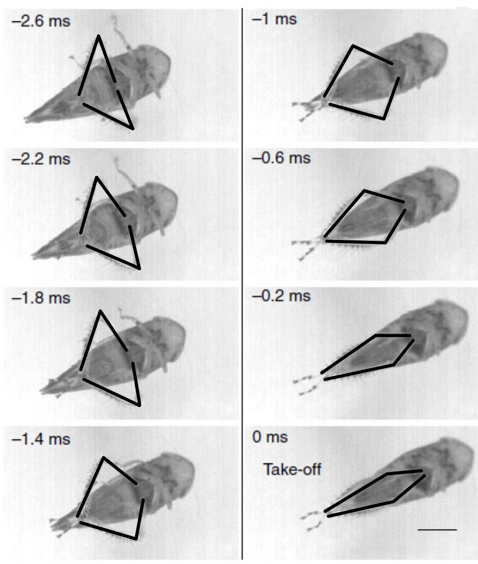

Figure 3: Sequence of Motion of the Hind Legs of a Leafhopper during Launch

Table 1 characterizes the jumping performance of notable high performance insects, which employ the jumping locomotion strategy. Of these, the best performance is attributed to the froghopper**.** The superior performance of the froghopper is the result of the bending and rapid release of the pleural arch, akin to a crossbow, that is attached at the hip to the hind legs, shooting them into the ground. They are capable of accelerations of $5400ms^{-2}$, and a best take off from the ground within 0.875 ms [11]. Figure 3 shows a partial sequence of the leafhopper's jump. The hind legs have been highlighted to show their motion with respect to time. The leafhopper employs a much flatter takeoff angle than the froghopper and is a heavier insect, resulting in reduced measured jumping performance. The method of power transfer and the morphology of the hind legs are very similar for both insects. The leafhopper has a peak acceleration of 1055 ms^{-2}[17].

DERIVED JUMPING MODEL

Research has been previously performed on the jumping performance of grasshoppers, froghoppers, fleas, and locusts to inspire new robotic designs [13, 23, 24, and 25]. The design proposed here is based generally on the morphology of the froghopper and the leafhopper insects. Figure 4 shows a schematic for the jumping model. Simplifications to the design include attaching the two legs at the hip and ankle joints, effectively transforming the mechanism into a symmetric four bar structure. This incorporates symmetry and synchrony between the two individual legs into the model design, and allows shared actuation between the two legs. It also enables simpler mechanical replication.

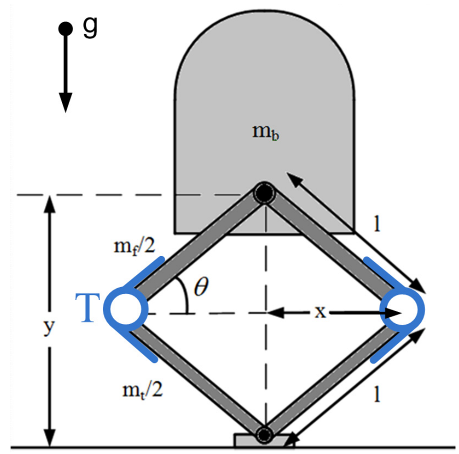

Figure 4: Bipedal Jumping Model with Elastic Energy Storage Elements

Various jumping models have been presented in the past, such as the ones presented in [19, 26, 27, 28]. The work presented here follows modeling principles previously presented, particularly by Alexander in his pioneering work on biological bipedal models [19]. Our model is unique in that it has been derived from leafhopper kinematics, and modified to include mechanical energy storage elements.

For the purposes of dynamical analysis of the jumping system, two-dimensional vertical motion is considered. The discussion can readily be extended to three dimensional ballistic jumping through the incorporation of an orientation angle, but for our purposes this is unnecessary since it has no effect on the system dynamics except for the addition of a linear horizontal velocity component.

For the purposes of deriving a mathematical model, we assume no friction occurs at the joints, since this is a factor which is practically minimized through the use of bearings and indirect coupling between the actuator and jumping mechanism. This aspect will be discussed in the final section of the paper. Additionally, air drag effects are not taken into consideration since the model describes a pre-launch analysis of a legged jumping system, and air drag effects would be minimal in this case. We also assume no slippage at the foot-ground interface.

The model comprises of a body of mass m_b with a center of mass at a height y from the ground. Making a point mass assumption for the links, each individual femur has a mass of $m_f/2$ assumed to act at the mid-point of its length at a height of 3y/4. Similarly, each individual tibia has a mass of $m_t/2$, acting at a height of y/4. It is assumed that the center of mass of the body lies at the same height as the hip joint. The angle θ is half of the angle between the femur and the tibia and x is the distance of the knee from the centerline of the body.

The following geometric relationships can readily be established for the system:

$$y = 2l\sin\theta \quad (7)$$

$$x = l\cos\theta \quad (8)$$

$$\dot{y} = 2l\dot{\theta}\cos\theta \quad (9)$$

$$\dot{x} = -l\dot{\theta}\sin\theta = -\frac{1}{2}\dot{y}\tan\theta \quad (10)$$

$$\dot{\theta} = \dot{y}\sec\theta / 2l \quad (11)$$

This model assumes that all energy has been stored in the energy storage element, and is about to be released to the system at t=0. Upon energy release, a torque T is applied to the knee joints with a corresponding angular velocity of $2\dot{\theta}$ for each joint. When this energy is released, the rate of work done by the acting torque on both joints is equal to the rate of change of kinetic and potential energy of the system:

$$4T\dot{\theta} = \dot{P} + \dot{K} \quad (12)$$

The moments of the inertia of the femur and tibia of each leg are $m_f l^2/24$, $m_t l^2/24$, respectively; and the respective vertical and horizontal velocities for each femur and tibia is $3y\dot{\theta}/4$ and $\dot{y}/4$, $\pm\dot{x}/2$. Therefore, the kinetic energy for the system at time t can be expressed as:

$$K = \frac{1}{2}(m_f + m_t)\left(\frac{\dot{x}}{2}\right)^2 + \frac{1}{2}\left(\frac{\dot{y}}{16}\right)^2 (16m_b + 9m_f + m_t) + (m_f + m_t)(l^2\dot{\theta}^2/24) \quad (13)$$

Using equations (10) and (11) to eliminate $\dot{x}$ and $\dot{\theta}$, the kinetic energy can be expressed as:

$$K = \left(\frac{\dot{y}}{24}\right)^2 (12m_b + 7m_f + m_t + \tan^2\theta(m_f + m_t)) \quad (14)$$

The potential energy for the system is:

$$P = \frac{gy}{4}(4m_b + 3m_f + m_t) \quad (15)$$

For simplicity, we define:

$$m_1 = 4m_b + 3m_f + m_t \quad (16)$$

$$m_2 = m_f + m_t \quad (17)$$

$$m_3 = 12m_b + 7m_f + m_t \quad (18)$$

Using equations (16)-(18), the time derivative of equations (14) and (15) can be expressed as:

$$\dot{K} = \dot{y}\ddot{y}(m_3 + m_2\tan^2\theta) + \frac{\dot{y}^2}{24}(2m_2\dot{\theta}\tan\theta\sec^2\theta) \quad (19)$$

$$\dot{P} = g\dot{y}m_1/4 \quad (20)$$

Using (19) and (20) with (12) and rearranging, the following equation is obtained for the vertical acceleration:

$$\ddot{y} = \frac{1}{2l(m_3 + m_2\tan^2\theta)}(48T\sec\theta - 6m_1 gl - m_2\dot{y}^2\tan\theta\sec^3\theta) \quad (21)$$

This equation describes the motion of the hip joint from the initial release of energy to the system. The condition for the loss of ground contact is when y>2l.

The force acting on the ground is the sum of the body weight and the force due to acceleration. When this force becomes zero, the body weight is countered by the stored-energy induced acceleration, and ground contact is lost. This is expressed as:

$$F_g = mg + \frac{1}{4}m_1\ddot{y}(t) \quad (22)$$

In order to characterize the applied torque on the system, and keeping in mind the eventual purpose of using these principles for the design of a robotic system, the energy storage elements in the knee joints are modeled as torsion springs. Then the torque T(t) acting on the system can be expressed as:

$$T(t) = 2k(\theta_0 - \theta(t)) \quad (23)$$

where θ_0 is the half-angle for an un-deflected spring, and k is the spring stiffness coefficient. In this way the model can be used to identify torsion spring parameters required for the performance of the mechanism. Using equation (23) with equation (21), the specific parameters, such as leg length, mass, and spring constants required to achieve a desired jumping performance can be evaluated.

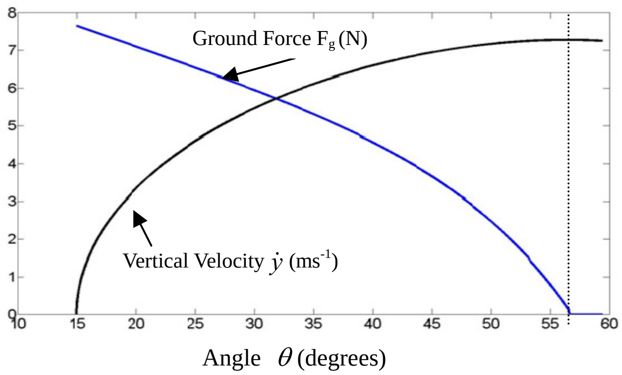

Figure 5: Variation of Ground Force and Vertical Velocity with Angle θ

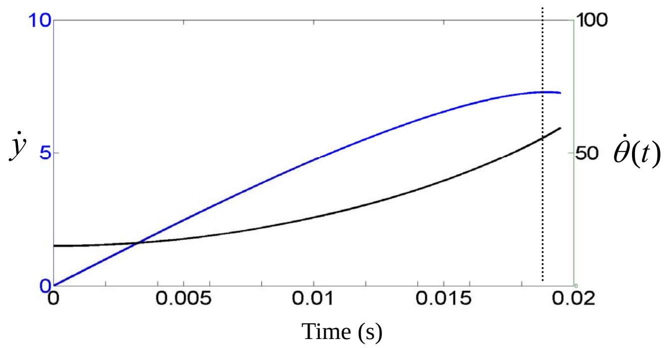

Figure 6: Variation of Vertical and Angular Velocity of the Center of Mass with time

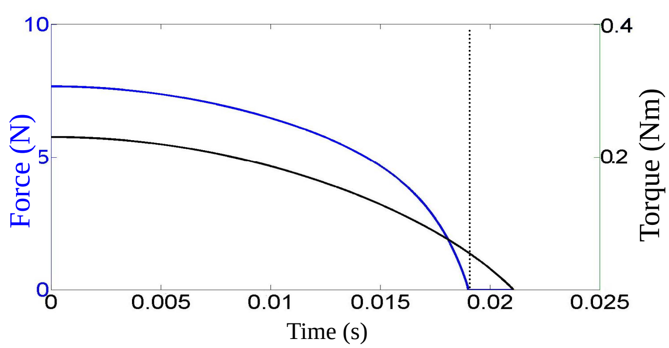

Figure 7: Variation of Torque and Corresponding Ground Force with time

The velocity at which ground contact is lost is the takeoff velocity for the body, after which the system will follow a ballistic trajectory as described in Section 1. Given the various parameters involved in the vertical jumping model, the maximum height reached by the center of mass is given as:

$$y_{\max} = y_0 + \frac{1}{32g}\left(\frac{m_1 \dot{y}_o}{m}\right)^2 \qquad (24)$$

where y_0 is the center of mass location at loss of ground contact and $\dot{y}_o$ is the corresponding velocity. Equation 24 relates the presented jumping model to its eventual ballistic trajectory.

Using numerical simulation software (MATLAB), the behavior of the system can be analyzed. To this effect, the following dimensions were chosen to assist in the eventual design of a miniature jumping robot: m_b=0.01kg, m_f= m_t=0.005kg, l=0.07m, k=0.12N.m.rad^{-1}, θ_0 = 75 degrees, $\theta(0)$=15 degrees. The masses and length are based on current jumping robots in practice [7, 13, 23, 25], while the spring stiffness and values for the angles were selected to ensure maximum force and angular deflection is imparted to the ground before takeoff is achieved. A simulation was run using a time step of 0.1 ms. The results are presented in Figures 5-7. The dashed lines represent liftoff from the ground.

Figure 5 shows the variation in the ground force and vertical velocity of the center of mass through the angular range of motion of the system. Lift off is achieved at the point where the ground force is zero, or according to equation (19), when the weight of the system is countered by the vertical acceleration. The corresponding velocity is the takeoff velocity of the system. This velocity combined with Equation 24 provides a measure of the jumping height of the system.

Figure 6 shows the linear and angular velocity variation of the center of mass versus time. The time taken to achieve lift off is 19ms, with the corresponding vertical velocity value as 7.28ms^{-1}.

The ground force starts at a maximum and then steadily reduces. This is because as the system is released from the charged state and the torsion spring unwinds, the energy stored in it reduces from a maximum value, directly affecting the generated forces. Figure 7 shows the torque due to the torsion springs variation with time and the corresponding ground force. At a torque value of 56 Nmm, equation (19) reduces to zero and takeoff is achieved.

This model defines fully a legged jumping mechanism, which uses torsion springs as the elastic storage elements. Simplifying assumptions include an omission of frictional force effects as well as vibrations and multiple ground impacts during takeoff. These issues will be analyzed in the future by further refining the model and studying a physical jumping prototype.

As previously stated, the analysis begins at the time where the energy from the spring is first released, under the assumption that the spring has been fully charged. The charging of the spring can best be performed by coupling the jumping mechanism with a power source, which for a mobile robot would be a DC motor. The following section explores few ways in which this coupling could be achieved.

COUPLING BETWEEN ACTUATOR AND JUMPING MECHANISM

This section will illustrate a practical embodiment of the previous discussion. The type of jumping system studied here operates on the principle of slow charging of an elastic element using an actuator, followed by a very rapid high powered release of that energy. This requires that the coupling between the output of the motor-gearbox and the input of the leg module must be discontinuous.

Previously constructed charge-and-release jumping systems have achieved this primarily through a cam-follower mechanism [30, 13, 23, 25]. The cam follower principle is to connect a specially designed variable-radius cam to the output of the motor gearbox. The follower is connected to the leg element. A schematic showing one possible configuration is shown in Figure 8 [23]. When the motor rotates, the follower that is connected to the hind leg travels around the cam and charges the spring.

A cam-follower system is used because at a certain point, which corresponds to maximum charging of the elastic element, the follower can disengage from the cam, allowing the leg mechanism to accelerate rapidly and deliver the required jump thrust. The acceleration distance is the dotted line shown in Figure 9. In principle, the cam is designed so that the force applied by the torsion spring through the follower remains perpendicular to the surface of the cam, and its scale is influenced by the acceleration distance required to impart a prescribed force.

Another method is through the use of a discontinuous gear [23], in which the gear teeth are placed along arcs rather than along the entire circumference of the gear, allowing discontinuous coupling. The primary concern with this design is that the size of the gear needs to be substantially large in order to ensure full spring charging occurs before decoupling. The application of these two methods for energy transfer will be investigated further in order to attain optimum design of a jumping machine.

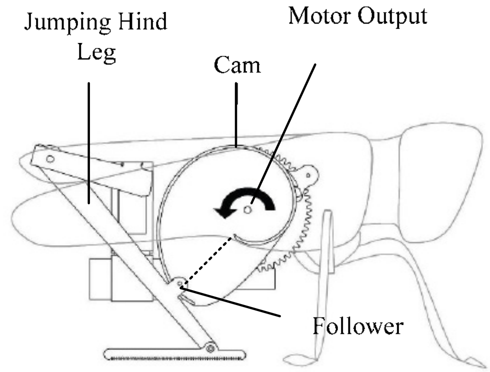

Figure 8: Jumping Model using Cam-Follower Principle

CONCLUSION AND FUTURE WORK

Jumping in nature is an efficient and interesting means of locomotion, which allows miniature creatures to accomplish remarkable dynamics. The application of similar principles in robotic systems would enhance both robotic mobility in rough terrain, and the range of tasks that mobile robots can perform.

This paper presented an investigation into jumping locomotion. Several insights into the principles of ballistic jumping are highlighted. A review of jumping insect morphology was performed to determine the principles under which successful jumps are performed. A simplified mathematical model, based on the jumping dynamics of the froghopper and leafhopper, was developed and presented. The model assumes that torsion springs are applied to the knee joints as the energy storage modules of the jumper, and derives the system dynamics. Relationships of interest, such as mass distribution effects on efficiency, the effect of the spring stiffness and leg length on the generated forces, as well as governing equations describing the motion of the system are presented. This model will provide a basis upon which the design of a jumping mechanism can be performed.

Our future work will include refinement of the model by including other effects, such as friction effects in the mechanical system as well as drag, vibrations, constraints imposed through stresses in the structure, and investigating other energy storage options such as linear springs. Further investigation of actuator-mechanism coupling will be performed, and the model will be expanded to incorporate the effect of different types of actuation.

Research is presently ongoing to develop methods that will minimize impact forces when a jumper returns to the ground as well as maintaining pitch stability in flight. Another bioinspired approach offers a unique solution – the use of foldable wings to allow unpowered gliding. This will increase flight duration and reduce impact damage. Combining jumping and gliding systems to create a light weight rough terrain mobile robot is the eventual aim of this research, and the jumping model presented here is an important step in that direction.

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