Biologically Inspired Legs for UAV Perched Landing

Arjun Nagendran[1], William Crowther[2] and Robert C. Richardson[3]

***Abstract*—Unmanned Air Vehicles (UAVs) are extensively deployed in surveillance and reconnaissance missions, involving gathering of data and delivery of payloads to remote places. However, they are limited in their ability to collect detailed information due to the short duration of their missions. The effectiveness of UAV missions could be significantly enhanced if UAVs had the ability to land in the target zone on buildings or roof tops and survey the surrounding environment rather than flying overhead. In this article, the concept of using a biologically inspired leg-based landing system for UAVs is presented. Stages of the landing maneuver, flight trajectories and proposed controllers are evaluated through simulations; results are analysed to show that a perched landing for UAVs can be successfully performed with dedicated hardware based on high frequency control loops.**

***Index Terms*—Unmanned Air Vehicle (UAV), Robotic Leg, Autonomous Landing.**

I. Introduction

The landing and looking maneuver, which is known as "*perch and stare*," assists the air vehicle in gathering detailed information over long periods, increasing its operational value. Furthermore, it offers a static perspective from which data such as video or images can be gathered, resulting in improved analysis and processing of results. An illustration of a UAV with biologically inspired legs is shown in Fig.1.

(a) (b)

(a) In-flight (b) Close-up view of the landing mechanism.
Fig.1. An illustration of the biologically inspired landing mechanism.

UAVs successfully use dedicated runways and artificially flat terrain (such as roads) for their launch and retrieval; however, their availability is limited. There is a need for alternative systems and techniques for more widespread usage of UAVs. The vertical take-off and landing capabilities of Mini Rotorcraft UAVs (Mini-RUAVs) deliver the required flexibility for surveillance and with a rotorcraft platform it is possible to hover and fly at low speed [1]. However, rotorcrafts (1) can be noisy, which may be undesirable in stealth environments, (2) cannot operate long distances, and (3) offer a challenge due to their limited payload and complex dynamics [2]. An integrated system consisting of an UAV and an Unmanned Ground Vehicle (UGV) [3] enables an UAV to be launched, recovered, and refuelled and allows an UAV to be deployed at a greater distance from operation personnel, thereby reducing risks to the ground crew. UAVs provide advantages such as speed of operation, overhead view, long communication range, and the ability to bypass terrain hazards while an UGV is capable of carrying heavy payloads and supply power. This approach requires a high degree of cooperation between an air vehicle and a ground vehicle while they operate in tandem to successfully complete missions.

The ability of UAVs to take-off vertically and land eliminates the need for runways /large landing zones and also offers flexibility in terms of hovering capability and translation in three dimensions. The hovering and landing control of a Vertical Take-Off and Landing (VTOL) aircraft using inertial optical flow (vision-based) is discussed in [4]. However, the time of flight of a VTOL vehicle is dependent on the weight of its payload. For a given payload, fixed wing aircraft can fly longer distances than VTOL aircraft.

Parachute recovery can be used as an emergency recovery method to minimize the damage to UAVs during a mishap [5]. If the undercarriage of UAVs contains sensors and other instruments, a parachute can be deployed from underneath UAVs causing the vehicle to invert itself and land, thus protecting sensitive equipment present underneath the vehicle. However, when a parachute is deployed, there is a transition from horizontal motion of the vehicle to vertical motion causing instability or oscillations of the vehicle [6]. Parachutes are affected by crosswinds and it is difficult to accurately determine the landing point due to sway. The possibility of the vehicle landing at any angle, and not necessarily flat, means that the vehicle design must take into account, ground impact heading in any direction [6]. Since typical descent rates for parachute recovery systems are around 5 m/s, it is likely that the horizontal component of velocity could be greater than the vertical component, resulting in the need for a good impact attenuator design.

Capture nets are another method commonly used to retrieve

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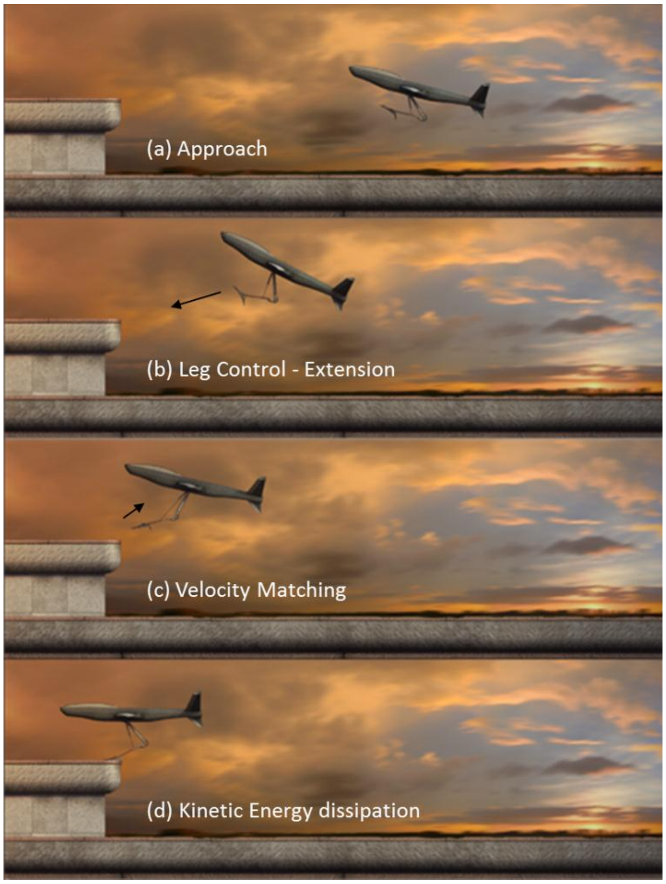

Fig.2. Stages of the perched landing maneuver.

UAVs. UAVs fly into a large net positioned at a specific location autonomously or through operator intervention in the form of radio control. A detailed description and analysis of geolocation of radio-frequency signals can be found in Dr. Progri's book on *Geolocation of RF Signals—Principles and Simulations* [7] which can be precisely used to identify the position and localize UAVs. These techniques can be beneficial in determining the maximum range of communication during deployment scenarios. The fixed location; however, limits the retrieval area of UAVs. Additionally, there is a large rate of change of momentum of a vehicle on impact which can cause substantial damage to UAVs and the on board equipment. A similar method of retrieval of UAVs is by using grappling hooks and cables [10]. In cases where terrain does not permit the recovery of air vehicles by any of the above mentioned methods, mid-air recovery or air to air recovery systems are used. The method is very expensive and is used only if the vehicle being recovered is extremely valuable [5].

II. Perch and Stare Maneuver

A potential solution to the short-comings with existing launch and retrieval methods is the design of fixed wing UAV landing systems capable of *perch and stare*. This provides UAVs with the ability to land in unknown environments through the use of legs to cushion the impact and perform a successful perched - landing maneuver. A successful landing maneuver consists of several stages Fig.2.

Approach: The first stage is the initial approach. This is the stage where an UAV has to identify a suitable perch and make its approach towards the perch.

Control of approach velocity: The second stage involves an UAV performing a suitable maneuver so as to minimize or optimize its horizontal and vertical velocities. It may involve flaring (increasing the angle of attack) to covert horizontal velocity to vertical velocity prior to the stage where the landing system takes over.

Extension of Landing Gear: Once the vehicle has been delivered to the desired position (pre-determined based on the reach-limits of the perched landing system) the landing gear extends to grab the perch. During the extension stage, it is essential to minimize the time taken by the landing gear to reach the perch, so as to minimize inaccuracies in position of an UAV or the flight path due to external factors such as wind. Velocity matching will be performed to minimize impact with the perch.

Absorption of Impact: When the end effector (gripper) makes contact with the perch, the overall dynamics change since the perch now becomes a part of the system. The contact force between the end effector and the perch is dependent on the mass and velocity of an UAV and the landing gear. The impact that occurs during landing must be minimized to prevent damage to the perch, air vehicle and its landing system. This involves dissipating the energy of the collision as work done through the application of a controlled force.

Controlled capture: Once the entire energy of the vehicle has been dissipated, the position and orientation of the vehicle must be controlled so that it achieves a statically stable configuration. This can be performed by a secondary controller on the landing system which applies the required correction.

III. Perched Landing Techniques

There are several methods of performing a perched landing maneuver that have varied requirements for approach velocity and impact absorption. A study reveals that pigeons generally exhibit two different forms of landing characterized by variations in their kinetic energy: low kinetic energy and high kinetic energy [8].

Low velocity landing: By flapping their wings during the descent, birds slow their approach to the perch and hover before the legs extend and grab the perch. The slow descent helps gain time during which the pigeons can minimize the error in placing their feet on the perch. The result is a low final kinetic energy landing in which experiments revealed that the pigeons exerted a force approximately twice their body weight while landing [8]. Although the method is proven to be energetically expensive, it reduces the risk of injury to the bird's legs due to torsional effects and impact forces. Only recently, a flapping wing flying robot called SmartBird has been developed [9]. While the engineering design is impressive, the vehicle's body itself is extremely lightweight (about 26 g) and consumes about 23 W in-flight. Payload and time-of-flight are therefore significant hurdles that must be overcome.

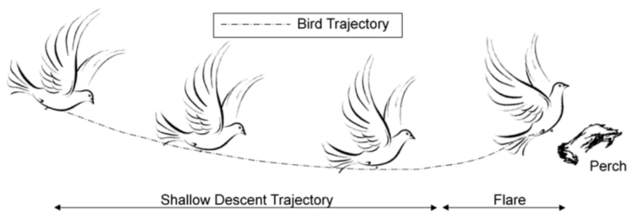

Fig.3. The high kinetic energy landing maneuver in birds.

Flare maneuver: Since hovering for a fixed wing aircraft is not feasible, an alternate approach is to use an extended flare maneuver to stall UAVs at the required position. This involves a relatively steep conventional approach, followed by an extended flare maneuver in which the aircraft increases its angle of attack [11] causing the horizontal velocity of the aircraft to be converted to vertical velocity. Eventually a stall condition (preferably close to and vertically above the perch) is achieved, followed by a "*free-fall*" stage during which the landing system can maneuver the aircraft onto the perch. This form of low kinetic energy landing reduces the force experienced by the air vehicle and minimizes the chances of damage due to impact. However, under *free-fall* conditions, the air vehicle is susceptible to external forces such as cross winds and is not as stable as it will be when in powered flight. Failure to grab the perch does not allow the air vehicle to abort the landing maneuver since it is not in powered flight.

High velocity landing: As an alternate, birds can also perform high velocity landings. To perform a high velocity landing birds follow a shallow descent trajectory either gliding toward the perch, or in powered flight. The approach has significantly more velocity than a low velocity landing, but reduced velocity compared to normal flight. When close to the perch, they increase their angle of attack, thereby causing a reduction in their forward speed. The method is proven to be energetically less expensive than the hovering maneuver. An illustration of this maneuver is shown in Fig.3.

Note that this must not be confused with the flare maneuver described previously. This is a high kinetic energy landing, with the flare helping to reduce velocity. As a drawback, the high speed of approach toward the perch requires accurate positioning of the feet, especially on relatively small perches. The force exerted on the perch during high velocity landings (more kinetic energy) is found to be about eight times the body weight of the pigeons, as opposed to about twice the weight exerted during the low kinetic energy landings [8].

If external factors such as strong winds cause errors in the flight path, the air vehicle can abort either by performing a conventional turn to either side, or by climbing over the perch. In a more complicated case such as when the leg has already extended to grab the perch but missed, the flare maneuver can be extended, followed by "hammer head" turn maneuvers [11].

IV. Biological Inspiration for UAV Leg Design

Birds in general have the ability to control their descent (variation in height) by flapping their wings, and using flare maneuvers. The legs help compensate for positional errors and help cushion their landing and assist in take-off. It is therefore appropriate to design the landing system similarly, with the assumption that the flight controller can compensate for variations in height prior to landing through the use of thrust and breaking. UAVs with a capability to hover may still benefit from the use of legs, since this offers the capability to perch on relatively narrow structures.

The femur, tibia (fibula and tibiotarsus), and tarsus (tarsometatarsus) form the main skeletal structure of a bird's leg. The typical anatomy of a bird's leg, adapted from the Manual of Ornithology [12], is shown in Fig.4 alongside the robotic simplification. Reduced length of leg bones results in keeping the body of the bird closer to its perch, reducing the moments around the joints and therefore reducing the muscle force required by the bird to maintain its stable orientation and position [13], [14]. It has also been proven that short tarsi, in general increase a bird's stability on perches by keeping the centre of mass close to the perch [14]-[16]. However, the shorter the leg the less reliable the reach of the leg is and the more accurate the flight needs to be.

Zeffer and Norberg [14], in their work on leg morphology and locomotion documented the relation between the mass and length of the tarsometatarsus in several groups of birds that included birds of prey, walkers and hoppers. Noticeably, birds with lesser mass (kg) had relatively long tarsometatarsi (m) (mass-length ratio of 0.25 – 0.66 kg/m), while the heavier birds had shorter tarsometatarsi (mass-length ratio of 0.035 – 0.05 kg/m). Birds like the common pigeon, which can exhibit both high and low final kinetic energy landing maneuvers have a length-mass ratio of about 0.1 [8]. Cuckoos, for a range of body weights of birds (0.23-0.769 kg), have bone ratios of: femur (25-33%), tibiotarsus (40-44%) and the tarsometatarsus (22-31%) [17].

The lengths of the robotic leg can be chosen based on the amount of energy to be dissipated on impact with the perch, using the ratio presented here; i.e., for an UAV of mass 0.5 kg, link 1 can be chosen to be 0.2 m (40%) and link 2 can be chosen to be 0.15 m (30%). The mechanical leg is designed to be a two joint serial link manipulator, with 2 degrees of freedom as seen in Fig.4. Joint angles are assigned using the Denavit-Hartenberg (D-H) convention. Each link has a length L, distance to its centroid c (centre of mass), and independent angles θ. The subscripts 1 and 2 are used to denote links 1 and 2.

The aim of this work is to identify the challenges associated with perched landings and develop control schemes that will assist an Unmanned Air Vehicle in successfully performing a "*Perch and Stare*" maneuver. A simple leg design is chosen by studying the physiology of bird legs, and some of the forms of landing they exhibit. Control schemes for each of the various stages of the landing are proposed based on the requirements and their performance is analyzed with respect to the forces applied, positional accuracies, joint de-coupling and impact. It is expected that the design and testing of these controllers will provide a better insight into the requirements for a successful perched landing system.

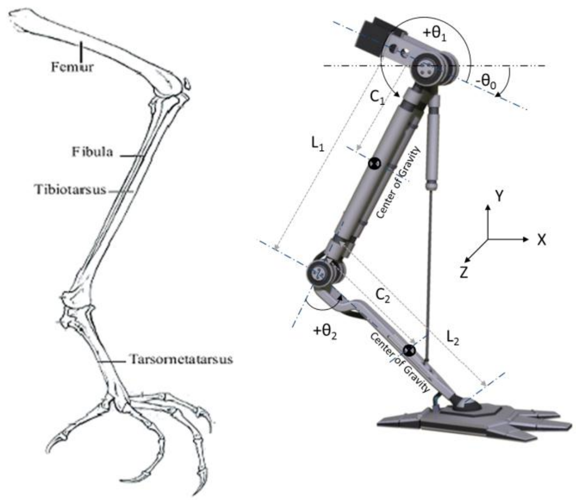

Fig.5. Comparison of the typical anatomy of a bird's leg (left), adapted from the Manual of Ornithology [8] and model of 2-joint mechanical leg (right) showing the centre of gravity of UAVs.

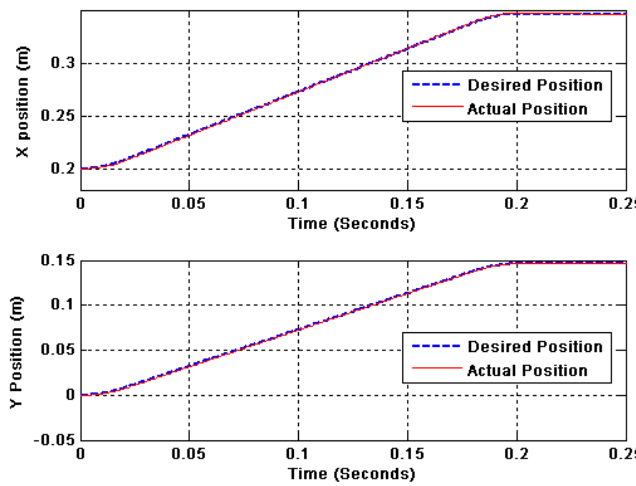

Fig.4. Desired and actual X and Y positions of the end effect during interpolated position control – Computed torque controller with secondary PID controller.

TABLE I
EVALUATING THE POSITION CONTROLLER

Evaluation Parameter	X(t)	Y(t)
Desired position(Time to achieve desired accuracy)	X(t=0.2s)=99%	Y(t=0.2s)= 99%
Square root of the (Sum of squared error (trajectory))	6.6191e-004 (m)	1.3e-003 (m)

V. Controller Design

Several independent controllers are proposed to enable UAVs with a robotic leg to perform perched landing maneuvers, including: control of the leg prior to landing, matching velocity of the leg and perch before landing, absorbing impact forces as the leg comes into contact with a perch and controlling the resting position at the end of capture. The required control scheme is kinematic, similar to that proposed in [18] where a robotic arm is required to catch a ball in-flight, but varies in terms of the dynamics of the system.

Position Controller – Extension stage of the landing maneuvers: It is assumed that once UAVs have been delivered to the desired location close to a perch, the coordinates of the perch relative to UAVs (position demand) are obtained using a sensor network [19] (not defined in the scope of this work, but could incorporate vision systems and whisker sensors). A computed torque controller with a secondary PID control to reject external disturbances is used to perform this task. The applied torque equations take into account, inertial forces, coriolis and centripetal forces as well as forces due to gravity. Additionally, any error between the desired and actual forces is compensated for using a standard PID controller, whose gain matrices can be chosen by solving an Eigen value assignment problem, where the natural frequencies of the system assume values that result in acceptable responses of the system states [20], [21].

The proposed control scheme was used to simulate the extension phase of the landing in simulation. The desired tracking tolerance (error) over the extension phase was ± 3 mm. The graphs shown in Fig.5 reveal that the end effector tracks the reference values that describe the ideal trajectory with an error of ±1 mm, as the metrics shown in Table 1.

Velocity matching: When the end effector of the landing gear makes contact with the perch, it has a velocity vector that includes its own velocity as well as the velocity of the air vehicle towards the perch. The difference in velocities between the stationary perch and the moving landing gear will result in impact that may cause the landing system to bounce off the perch, or damage the perch itself.

When impact occurs, a portion of the kinetic energy of the two bodies involved is lost as thermal energy. To minimize the velocity mismatch a smooth blend of velocities and positions is required. To ensure that the acceleration profile has a minimum jerk (derivate of acceleration), the desired trajectory is defined as a 5^{th} order polynomial. A minimum jerk profile [22] is characteristic of human hand motion during a majority of tasks, presumably due to the decreased strain on the joints. The accuracy of the velocity matching process defines a trade-off between the amount of kinetic energy loss and the permissible impact; a small amount of kinetic energy loss may in fact be beneficial, since this reduces the work to be performed by the leg - the impact however causes jerk.

Fig.6 shows the effector of velocity matching on the contact force—the better the velocity match, the lesser the force experienced.

Kinetic energy dissipation: The air vehicle will be brought to rest when its kinetic energy has been dissipated as work done by the landing gear. This requires the application of force through the leg, while taking into account the maximum possible deceleration tolerable by the air vehicle. Force control alone may be insufficient since it does not ensure that the kinetic energy of UAVs can be dissipated within the workspace limits of the landing gear. The dynamic relationship between the position of the landing gear and the force applied defines an impedance relationship [23]. If the leg controller exhibits pure spring behavior (no inertial or damping properties) it can be considered a stiffness controller.

The characteristics of this stiffness can be dynamically

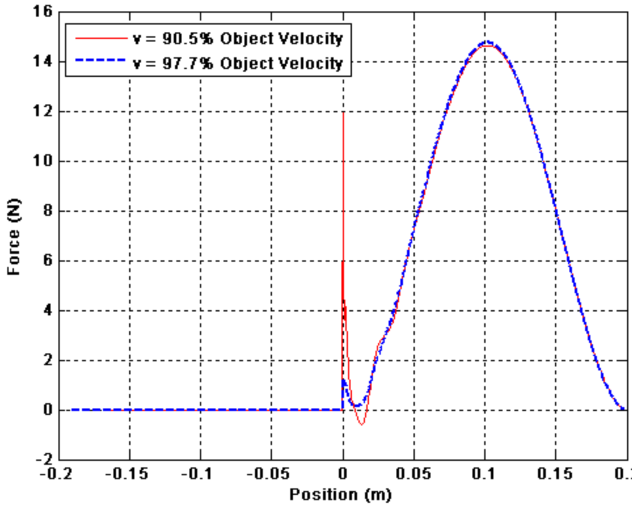

Fig.7. Force experienced during the combined process of velocity matching (prior to position being 0 m), on impact with the perch (at position 0 m), and while decelerating (next section).

varied during the landing depending on the computed kinetic energy of the air vehicle. This requires estimating the air vehicle's mass and velocity during every instant of the capture, for which parameter estimation techniques such as self-tuning and adaptive control can be implemented. The use of a bell-shaped stiffness control scheme to capture free flying objects has been discussed in [24] and shown to minimize the jerk and forces experienced during the capture. The area under the stiffness curve determines the total work done. In order to decelerate UAVs to a complete stop, the work done must equal its total kinetic energy. If the kinetic energy of UAVs is known prior to the capture, the parameters that control the stiffness relationship can be designed beforehand so that the area under the resulting bell curve is equal to the kinetic energy of the object. However, this may not be possible due to variation in parameters such as velocity during the approach. The kinetic energy of an UAV can be computed in real-time during the course of the landing, through the use of self-tuning and parameter estimation [25]. Assuming a high sampling frequency, the object's kinetic energy is computed from the forces being applied and the resultant position change in the leg [25]. The amount of force being applied is then scaled by the ratio of the current kinetic energy of the object to the remaining area under the curve (which originally equals the estimated kinetic energy on approach) at every sample instant. This is an adaptively varying control scheme that actively interacts with an UAV during its capture, and permits a non-linear stiffness relationship that may be similar to the role played by the muscles and tendons in a bird's leg.

Fig.7 shows the combined graph with velocity matching, followed by kinetic energy dissipation. The velocity graph reveals this reduction in velocity following impact. The entire landing maneuver is completed in about 1.5 s.

Control of resting position: It is desirable to finish the perch landing with the vehicle body at a specific location with respect to the leg and perch. Due to inaccuracies in the flight approach it is not possible to ensure a straight line approach to the ideal resting position.

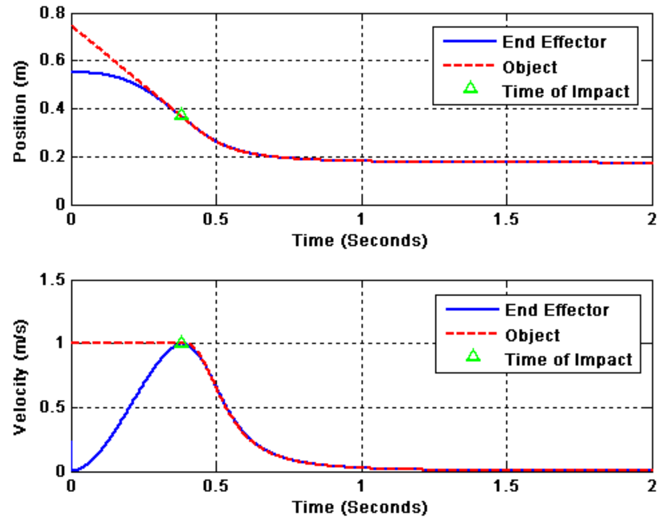

Fig.6. Relative position and velocity graphs of the perch and UAV during the landing maneuver.

It is possible to use the leg actuators to control position after the perch has been completed; however this may require more powerful actuators and is energy expensive. A better approach is to apply forces during capture to guide the vehicle to the resting position.

The resting coordinate can be chosen based on the effector it has on the static stability of the air vehicle after capture, or can be chosen as any coordinate that helps minimize the torques acting on the two joints on completion of the perched-landing maneuver. Capture coordinate tuning involves the controlled guidance of the end effector to the pre-chosen coordinate during the process of the capture. The desired co-ordinate behaves as a local attractor that gradually varies the distances over which the legs need to decelerate UAVs along each individual axis. This prevents an application of force along either axis that may result in jerk, instead naturally decreasing the deceleration force along one axis and allowing the other axis to control the motion vector. It must be noted that to guide an object to a rest coordinate, it is first required to ensure that the leg has sufficient kinetic energy (after impact) along each axis to reach the coordinate. The high kinetic energy in maneuvers implicitly ensures that this condition is satisfied, as opposed to the extended flare maneuver or hovering where UAVs vertically descends onto the perch.

VI. Conclusion

The ability of UAVs to perform a "*perch and stare*" maneuver could significantly enhance their effectiveness during surveillance and reconnaissance missions. In this work, the concept of a biologically inspired leg-based landing system has been presented. The controllers have been tested in simulation and designed to minimize the forces experienced by UAVs during the perched landing maneuver, which is significant considering the sensitive payloads carried by them. With accurate position control, velocity matching using a polynomial spline trajectory can be used to minimize impact with the perch. Cushioning the inside of the gripper

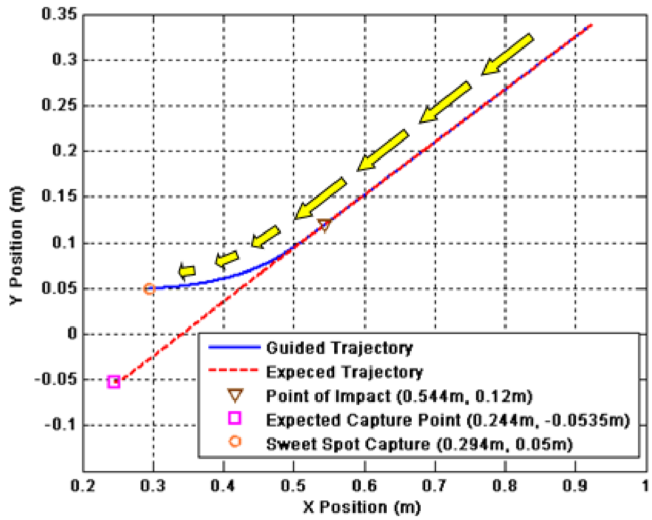

Fig.8. Expected and guided trajectories of the leg during the perched landing maneuver.

mechanism with a material that has spring-damper properties can help reduce the impact and prevent slip and bounce on contact with the target. Estimating the kinetic energy of UAVs during the capture provides the controller with sufficient information to vary the amount of force being applied in real time to decelerate it. By combining an adaptive bell-shaped stiffness controller and velocity matching scheme, a safe and successful perched landing maneuver can be accomplished. The required accuracy and high speed of operation required for this maneuver are limited by the performance of available actuators and the control bandwidth of the hardware. A video render of the perched landing maneuver is included as a part of this submission and can be found at [26].

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