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Landing and Perching on Vertical Surfaces with Microspines for Small Unmanned Air Vehicles

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Abstract We present the first results of a system that allows small fixed-wing UAVs to land and cling on surfaces such as brick walls using arrays of microspines that engage asperities on the surface. The requirements of engaging and loading the spines lead to an approach in which an open-loop pitch-up motion is triggered by a range sensor as the plane nears the wall. The subsequent dynamics result in a period during which the plane stays within an envelope of acceptable orientation and velocity (pitch from 60-105 deg, vertical velocity from 0 to -2.7 m/s and up to 3 m/s of horizontal velocity) that permit successful perching. At touchdown, a non-linear suspension absorbs the remaining kinetic energy to minimize peak forces, prevents bouncing and facilitates spine engagement. The total maneuver duration is less than 1 s. We describe the spine suspension and its analysis and present results of typical perching maneuvers (10 landings under autonomous control and 20 under manual control). Under calm conditions, the success rate for autonomous perching on building walls is approximately 80 %, the failures being attributed to erroneous wall detection. We conclude with a discussion of future work to increase the robustness of the approach (e.g. with wind) and allow subsequent take-offs to resume flight.

Keywords Perching · Landing · Vertical surfaces · Wall · Microspines · Adhesion · Suspension · Unmanned Air Vehicles · Endurance

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1 Introduction

Miniature unmanned air vehicles are becoming increasingly popular for military and civilian applications. However, they suffer from a relatively short flight time, can be difficult to land safely on the ground, and are vulnerable when parked. An attractive alternative is to let them do as many small flying animals do: take frequent short flights with periods of perching in between. In particular, it is useful for small fixed-wing planes to perch on vertical surfaces such as cliffs or the walls of buildings. Clinging passively to such surfaces, they consume little power, allowing them to remain for hours or possibly days as a stable platform for unobtrusive surveillance, inspection or environmental monitoring. Vertical surfaces are especially attractive because they are often relatively uncluttered and free from debris. In addition, if the plane perches under an overhang, it can ride out a storm in relative safety.

2 Related Work

Although the ability to land and perch on vertical building surfaces is, to our knowledge, new, it draws upon two previous areas of work: (i) fixed-wing planes that execute dynamic maneuvers for landing and perching (ii) climbing robots that use micro-spines or directional adhesion for attachment to vertical surfaces.

2.1 Landing and perching maneuvers

In prior work, perching has been studied mostly from the aerodynamics and control point of view. For example, in one approach, researchers [6] have used motion capture cameras (119Hz, sub-millimetre accuracy) to control an RC plane with an off-board controller for various indoor maneuvers such as flying in a room and using controlled hovering to land on a specially designed docking station. A similar system was used in [5] to create an accurate high-dimensional model of a glider during high angle-of-attack (AOA) maneuvers. This allows the plane to perform aggressive pitching maneuvers required to decelerate it to almost zero velocity before perching on a pole. Due to the challenge imposed by the very small target and the limited actuation control, the entire procedure was successful 20% of the time. In later work it was shown [14] that the glider becomes less controllable as its airspeed drops just before perching, even if a controllability is improved with a fixed propeller or thrust vectoring.

In other work, autonomous hovering has been demonstrated with fixed-wing aircraft [8,9,7]. The controller is based on the PIC16F87 and uses a Microstrain 3DM-GX1 inertial measuring unit (30 grams, 100 Hz update rate) to measure spatial orientation. The plane uses rudder and elevator to control pitch and yaw and has small propellers on the wing tips to control roll.

Still other work has focused on performing perching maneuvers using a morphing airplane [16,17,18]. Simulations show that pitching up the body while keeping wing and tail horizontal allows the plane to maintain control and create lift during the entire maneuver. This approach creates a shorter perching trajectory than one would require with a fixed-wing airplane although it adds some mechanical complexity.

Extensive biological research has been devoted both to flying and to ground locomotion. However, much less has focused on the physics of transitions that occur during perching. It has been suggested that flying evolved from the advantages of having only a small amount of lift to control and reduce landing forces [4]. An example of this phenomenon can be found in the flying squirrel: its low aspect ratio wing providing aerodynamic stability and lift at angles of attack up to 40 degrees. Furthermore, squirrels deliberately stall themselves prior to landing, allowing them to reduce by 60% their horizontal velocity before landing, while spreading the impact over all four limbs [3, 13].

In the present work we focus on a plane that, instead of perching on a wire, pole or docking fixture, lands on a vertical wall. As discussed in a later section, this approach provides different and possibly less restrictive constraints concerning the velocity of the plane at contact.

2.2 Vertical climbing robots

The mechanism by which the plane attaches itself to the wall is based on previous work on insect-inspired climbing robots that use arrays of directional spines in a compliant suspension [2, 15]. The spines are small and have tip radii ranging from 25 μm for relatively rough materials such as stucco to 10 μm for smoother materials such as cement or brick. Because each spine can only support a small load (1 N or less), many spines are used and it is the role of the suspension system to distribute the load among them. In comparison to other technologies such as suction, [10], magnets and pressure sensitive adhesives, spines have two main advantages: they require no power for clinging and they provide directional adhesion, which facilitates engagement and disengagement with minimal work [11]. However, to engage surfaces reliably, the spines require a particular approach trajectory. This is not difficult to achieve with a slowly climbing robot, but presents a challenge for landing and perching with an airplane.

3 Vertical Perching Strategy

The requirements for spine engagement translate to requirements for (i) the envelope of possible velocities and orientations of the plane as it approaches the wall and (ii) the mechanical properties of the suspension that connects the plane to the spined feet. In contrast to previous work on perching, we are not interested in contacting the surface at nearly zero velocity; the spines need to drag gently along the wall to engage asperities. A second difference with respect to previous work is that we do not assume high quality information regarding the plane velocity and orientation. We want a system with small and light sensors and a small CPU that can be placed onboard. We assume that once the wall is detected, the landing procedure will be mostly open-loop, with enough momentum to keep the plane from being highly sensitive to small disturbances.

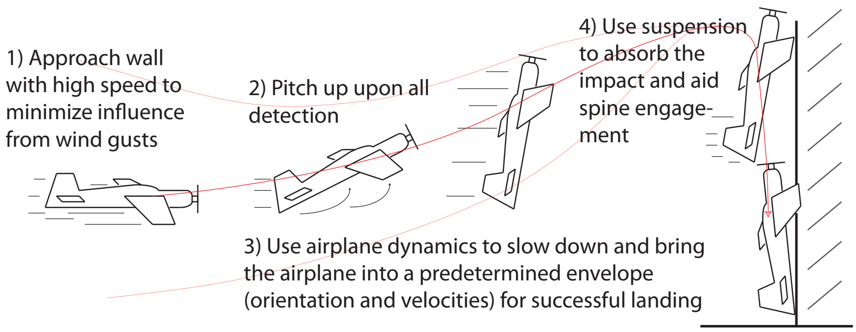

Fig. 1 Proposed landing sequence using the airplane dynamics to pitch up and relying on the suspension to provide the proper engaging motion on the microspines.

The general sequence, illustrated in 1, is: (1) fly toward the wall at cruising speed to minimize gust disturbances, (2) pitch up when a few meters away from the wall to rapidly slow down, (3) take advantage of the airplane dynamics to position it for landing while maintaining some forward velocity, and (4) to absorb the impact with a passive, nonlinear suspension that facilitates microspine engagement.

The focus of the work described in this paper is on the suspension in step (4) and the goal of the suspension design is to permit as generous an envelope of velocities and orientations as possible in step (3) while still ensuring spine engagement.

The airplane used for these experiments is a modified Flat-Out Flatana, designed for 3D maneuvers, low speed flight, and tight turns. For the experiments reported in this paper, the plane has been converted into a glider to simplify its design and reduce the number of components to be repaired after a crash; the motor has been replaced by an equivalent mass and only elevator control is used. A Paparazzi autopilot [12] has been added along with an XBee modem for telemetry, an LV-MaxSonar-EZ1 for wall detection, and a 3-axis accelerometer (ADXL300) and two 2-axis rate gyroscope (IDG300) for state sensing and estimation. The plane weighs a total of 375g.

4 Microspines and Suspension Design

Everything during the perching maneuver is done to bring the plane into a configuration that allows it to perch on the wall. It is thus important to understand the requirements of the adhesion system used, as different systems have different requirements and tradeoffs. Microspines have been chosen for this project as they can be used on a variety of surfaces [2,15], are lightweight, require no power, and provide directional adhesion, allowing repeated use and low effort for engagement and disengagement. This section explains their requirements for adhering to a vertical surface and details the strategies used to design a suspension satisfying the requirements for a range of initial velocities and orientations.

4.1 Microspine Requirements for Landing

The microspines are made of an array of small (≈15μm tip radius) spines that hang on surface asperities as shown on figure 2. Each spine has its own suspension to distribute the load and conform to asperities. In this design, a single spine is enough to hold the weight of the airplane but a total of 10 spines, distributed over two feet, are used for some redundancy and to account for the higher dynamic load experienced during landing.

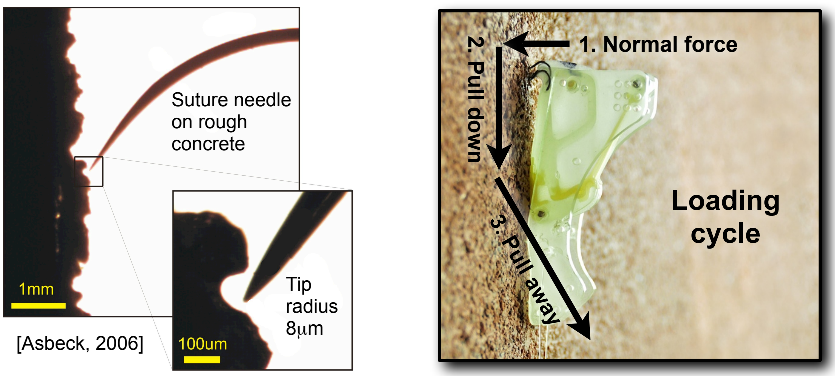

Fig. 2 The figure on the left shows the spine tip approaching a concrete surface. The figure on the right shows the loading cycle required by the spines.

One challenge in using spines is that they require a specific loading cycle, shown in figure 2, to operate properly. One must first apply some force toward the wall, to favor engagement, while dragging the spines down. It is then possible, while maintaining a downward force, to pull away from the wall. The higher the downward force, the higher the adhesion force available. The spine suspension design follows the general procedure discussed in [2] and shown on figure 3. It consists of an elastic linkage that is very compliant in compression (on the order of 5 N/m), in the direction normal to the wall on initial contact, to prevent bouncing. As the spine drags down the wall, it eventually (usually within a few millimeters of travel) encounters an asperity on which it can cling. At this point, a load can be applied primarily tangential to the wall, but with an outward tensile component as well. When pulled in this direction, the suspension is stiffer (on the order of 100 N/m) but compliant enough to promote load sharing between adjacent spines. For a given coefficient of friction and surface roughness, the ratio between the maximum normal and tangential force defines a fixed loading volume, shown on figure 3. As discussed later in Section 8, this means that for a plane to resist strong gusts of wind it will ultimately be necessary to use preloaded pairs of spines to increase the available normal force. The third criterion in designing the mechanism and setting the stiffnesses of the flexures is that the spines should not bend or rotate upwards as they are loaded, which could cause them to slip off any asperities that they find.

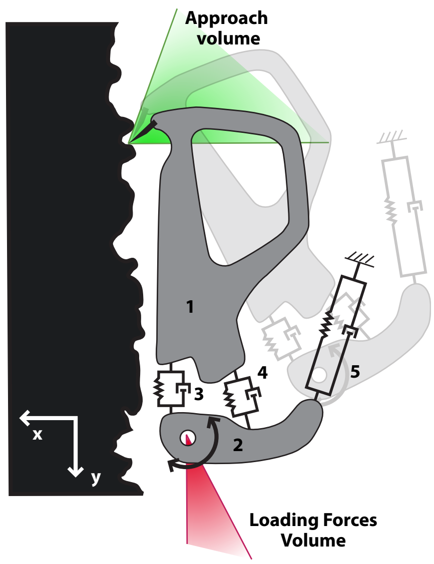

Fig. 3 Representation of the microspines. The spring elements 3 & 4 contribute to the tangential compliance, while element 5 provides the relatively soft compliance normal to the wall. The approach volume is mostly a function of the asperities' geometry while the loading volume depends on the coefficient of friction and the asperity geometry.

The ramifications of the spine design for the control of the airplane are that it should have a small velocity normal to the wall (to prevent bouncing) and a moderate downward velocity to load the spines once they make contact. In addition, the orientation of the plane should be maintained within some fixed range corresponding to desirable orientations of the spines as they contact the wall. In addition, it is desirable for the center of mass of the plane to be kept close to the wall after contact.

4.2 Preventing Vertical Rebound

Although the small elastic “toe” mechanisms holding the spines help to prevent bouncing in the direction normal to the wall, they have a very limited suspension travel (a few millimeters), requiring an additional suspension in the “legs” of the landing gear interposed between the spines and the plane. More significantly, there is the danger of rebounding in the vertical direction, parallel to the wall, where the velocities and forces are higher.

Following the observation during initial tests that vertical rebound was the main cause of failure, three design goals were formulated for a good suspension:

1. Minimize the maximum force (F_{max}) in the vertical direction to allow for a lightweight structure.
2. Minimize the suspension travel (-x).
3. Prevent spine rebound (negative vertical force) during the landing.

A solution satisfying these goals is to have a constant force for the full duration of the landing. Unfortunately, the force pattern that can be generated depends on the components available and, in the case of a small UAV, the task becomes challenging due to the size and weight constraints.

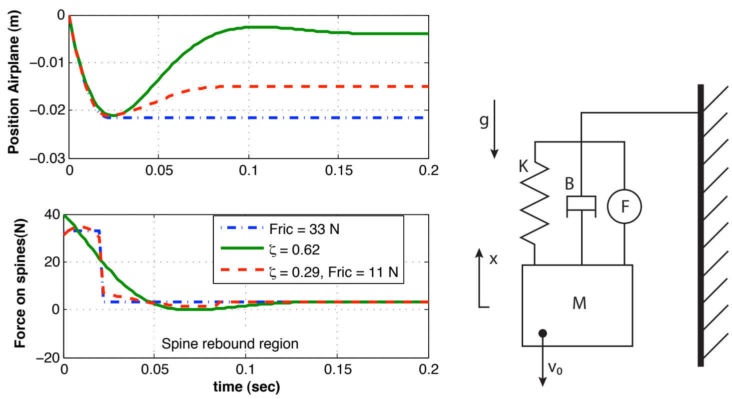

Fig. 4 In this one-dimensional model in the vertical direction, different passive suspension parameters create a range of performances, but only the blue curve minimizes displacement and maximum force, while preventing spine rebound. The model includes a mass subject to gravity and having an initial velocity, being slowed down by a suspension consisting of a spring, a damper and a Coulomb friction term.

In the case of a simple spring-mass-damper system subject to gravity and having an initial downward velocity, as illustrated in figure 4, it is possible to write the goals previously mentioned in a single cost function minimizing:

$$J = |\max(F)| + \lambda|\max(-x)| + |(F < 0) \times \min(F)| \quad (1)$$

where λ is a weighting factor that can be adjusted to trade-off between the maximum force and suspension travel criteria. A Nelder-Mead simplex can then be used to minimize this cost function. The resulting trade-off curve obtained by varying λ is shown in figure 5. This figure shows that as the maximum allowed displacement of the suspension is reduced, the damping ratio must be increased accordingly. This is due to the shorter landing time, corresponding to shorter suspension displacement, during which the damper can dissipate kinetic energy. This is unfavorable as a high damping ratio suspension creates a high initial force that decreases rapidly (see red curve in figure 4), requiring a sturdy structure to accommodate the initial force.

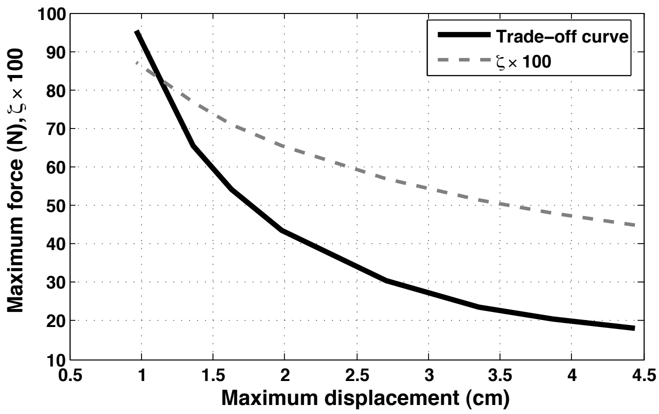

Fig. 5 Trade-off curve between maximum displacement and maximum force for a spring-damper suspension preventing rebounds. Also shown is the damping ratio required at any point in the trade-off curve. Results are shown for a 320g airplane subject to an initial velocity of -2m/s

4.2.1 Spring, Damper and Coulomb Friction

In order to prevent the high initial force caused by a strong viscous damper, a pure coulomb friction suspension could be used. However, a pure coulomb friction also has practical drawbacks: it does not return to a single equilibrium position after landing and it is difficult to adjust the level of friction precisely. In addition, it requires a hard stop to limit the suspension travel. Fortunately, it is possible to combine coulomb friction with a spring and damper and still obtain a near optimal solution.

Knowing the desired maximum force (F_{max}), the touchdown velocity (v_i), the desired spring stiffness (k) and assuming that we can design a near constant force suspension, the trajectory of the airplane during landing can be approximated by a mass subject to constant acceleration:

$$v(t) = \left(\frac{F_{max}}{m} - g\right) t + v_i \tag{2}$$

$$x_{max} = \frac{1}{2}\left(\frac{F_{max}}{m} - g\right) t^2 + v_i t \tag{3}$$

Combining, we get an expression for the maximum compression of the suspension when $v(t) = 0$:

$$x_{max} = -\frac{v_i^2}{2}\frac{m}{F_{max} - mg} \tag{4}$$

To obtain an approximately constant force profile on the spines during the landing, the initial force, a combination of damper and coulomb forces, must be equal to the force at maximum compression, which is a combination of the spring and coulomb forces. Thus:

$$F_{max} = -kx_{max} + F_{fric} = -bv_i + F_{fric} \tag{5}$$

$$\tag{6}$$

From these equations, it is possible to solve for the required damping coefficient (b), the friction force (F_{fric}) and the damping ratio (ζ):

$$b = \frac{kx_{max}}{v_i} \tag{7}$$

$$F_{fric} = F_{max} + kx_{max} \tag{8}$$

$$\zeta = \frac{x_{max}}{2v_i}\sqrt{\frac{k}{m}} \tag{9}$$

A suspension designed using these criteria provides an almost constant force during landing. It is more robust to variations in initial velocity and returns to its default state as long as $F_{fric} > -kx_{max} - mg$ (where $x_max < 0$). As an example, for a maximum force of 31 N, a spring stiffness of 860 N/m and a initial speed of -2 m/s as parameters, these equations lead to a damping ratio of 0.29, a friction force of 11.2N and a maximum displacement of 2.3 cm.

4.3 Non-Linear Damping

While the previous sections show what parameters are necessary to provide good spine engagement, the derivation assumes constant value parameters that can be varied independently. Furthermore, the size and weight constraints on a small UAV severely limit the kinds of components that can be used in a suspension and favor lightweight viscoelastic materials.

However, some viscoelastic materials have non-linear properties that can be advantageous for lightweight suspensions. It can be shown, as in [1], that in the case of a simple spring-damper suspension subject to an initial velocity, the force on the spines would be constant if the damping coefficient is equal to $b = (F_{max} - kx(t))/v(t)$. This means that a low damping coefficient is desirable initially (high velocity at contact), and that it should increased as the plane slows down.

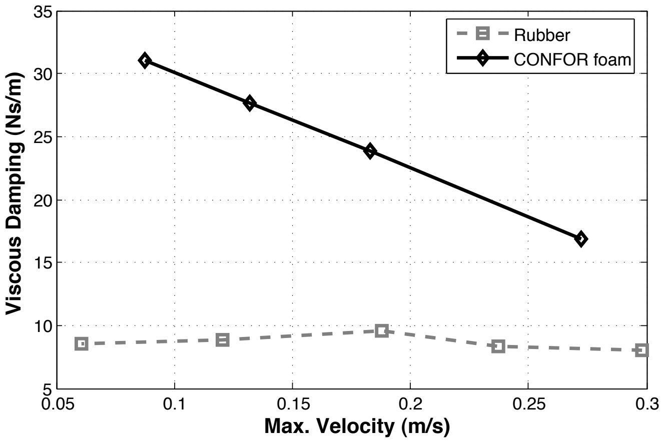

Fig. 6 The damping coefficient of materials varies in different ways. Rubber shows a near constant damping coefficient for the range of speed experienced by the suspension while pink CONFOR foam damping is significantly lower at high velocity.

An example of this kind of material can be found in CONFOR foam, a slow-recovery urethane foam. Although not having exactly the damping characteristics required to provide a perfectly constant force, figure 6 shows that this material has a damping coefficient that decreases with increasing speed compared to the near constant damping of rubber. These materials were tested by subjecting them to a sine wave of varying amplitude, to keep the amount of damping and spring force roughly proportional during the testing. An Adept One robotic arm was used to generate the motions and forces were measured with a JR3 wrist force sensor. The section tested measured 25x25mm for pink CONFOR foam and 7x2mm for the rubber, both 10cm in length.

4.4 Suspension testing

Several foam suspensions were built and tested to obtain a rough estimate of the envelope of possible landing configurations, as the one shown in figure 7. No extensive characterization has been done yet, but the maximum values of orientation and velocity were recorded from 30 flights and are summarized in table 1. The lower limits of pitch angle and v_y are currently set by the ankle design joint placement and could be improved in future designs.

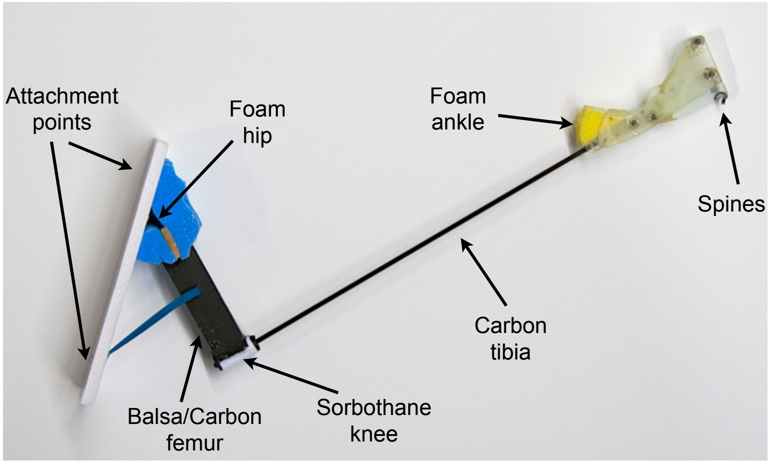

Fig. 7 Suspension made of slow-recovery urethane foam. The ankle joint provides a fast response to the surface profile, while the hip and knee joint absorb the impact without any rebound.

The suspension could probably allow landing with a horizontal velocity, v_x, higher than 3m/s, but this hasn't been observed due to drag at high pitch angles drastically decelerating the plane; initial velocities have simply not been large enough to result in v_x above 3m/s at contact. Pitch angles higher than 105 degrees also have not been observed, as the plane tends to return to 90 degrees pitch.

Table 1 Values of orientation and velocity observed at touchdown during 30 successful landings on concrete wall. Minimum pitch and minimum v_y are currently limited by the linkage design.

Envelop parameters	**Minimum**	**Maximum**
Pitch	60 deg	105 deg
Pitch rate	0	200 deg/s
v_x	-	3 m/s
v_y	0 m/s	2.7 m/s

5 Airplane Trajectory

The relatively wide ranges of orientation and velocity at which the plane can perch impose relatively few constraints on the trajectory. This has allowed us to use the natural dynamics of the airplane platform. As shown in figure 8, the natural response of the plane flying at about 9 m/sec to an elevator up (45 degrees) command is as follows:

- The plane rapidly pitches up to 60 degrees (minimum pitch angle for perching) in about 4m, or 0.35 sec, gaining little altitude.
- The drag created by the high pitch angle rapidly slows down the x velocity of the plane to about 3 m/s. Past 40 degrees of pitch, the pitching moment becomes negative and slowly reduces the pitch rate.
- The plane continues to pitch and maintains a small, positive x velocity, ready for touchdown.
- This continues for a total travelled distance of about 2 m, or 0.5 sec, before the gravity has increased the downward velocity to a point outside the perching envelope.

It is interesting to note that the approach is very short, under 1 sec, minimizing the period of time during which a disturbance could affect the plane. Furthermore, the plane initially flies toward the wall at 9 m/s and always maintains a slight forward velocity, minimizing the effect of any disturbances encountered.

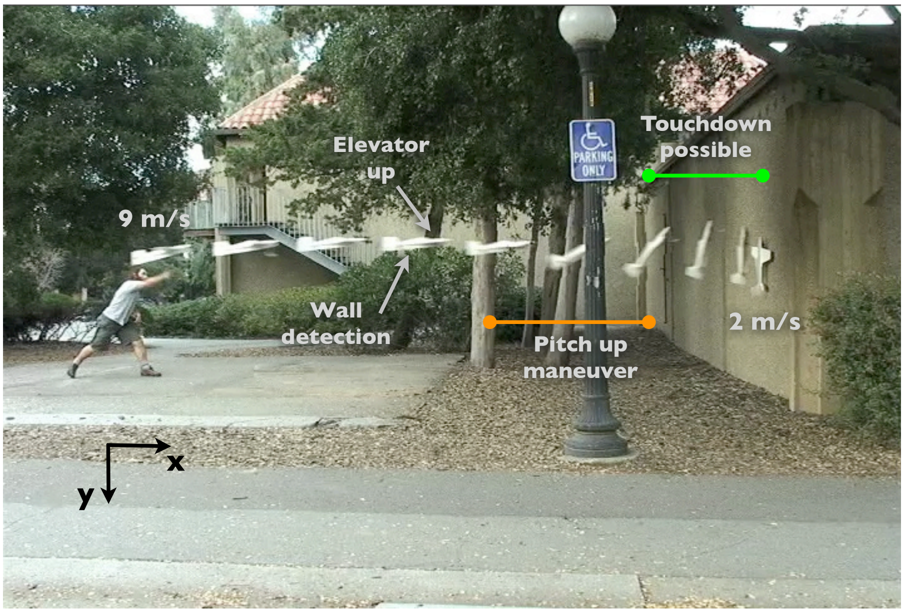

Fig. 8 Camera frame grab (7.5Hz) showing the perching maneuver. The glider is launched at 9 m/s, detects the wall 6 m away, pitches up and slows down to 2 m/s before touchdown. During touchdown, the suspension absorbs the impact and provides the necessary motion to engage the spines on the wall.

This trajectory is possible for two reasons: the large elevator of the plane and the slight negative moment present at high angle of attack. As shown on figure 9, this glider flies at a trim pitch of 15 degrees but can generate a large pitching moment by commanding the elevator to a 45 degrees position. With the elevator up, the pitching moment remains positive up to about 40 degrees, and then becomes slightly negative, slowing down the pitching motion. The key to a successful maneuver is to create just enough initial angular momentum to reach a pitch angle of 90 degrees with zero pitch rate.

One could also think about a two step maneuver: commanding the elevator up to its maximum to create a higher pitching rate, followed by a second elevator command to slow down the plane to zero pitch rate when a pitch of 90 degrees is reached. This would have the advantage of keeping the maneuver as short as possible, but would require pitch sensing and hasn't been implemented yet.

6 Sensors and Control

The trajectory shown on figure 8 is particularly simple from a sensing point of view. Because the plane stops its pitching motion when it approaches 90 deg (a perfect pitch angle for landing), this maneuver can be executed without any pitch sensor. The only sensing requirement for a fully autonomous landing is to measure the distance from the wall to trigger the maneuver at the right time. Because of the large available touchdown region, the sensor doesn't need to be particularly accurate nor to monitor the wall position as the plane is pitching up. Furthermore, since the wall distance sensor is only used for triggering the maneuver, any time delay in the sensor does not affect the maneuver as long as the delay is known.

Considering the delay in the servo controlling the elevator (roughly 0.1 sec, or 1 m), the distance to pitch up (4 m) and trying to land in the middle of the touchdown region (2 m wide), the maneuver should start from about 6 meters away from the wall. The entire maneuver is open-loop, consisting of just moving the elevator up to 45 deg when the plane is approximately 6 m away from the wall. Fortunately, the LV-MaxSonar-EZ1 ultrasound sensor has a range of 6.45m, a 20Hz update rate, is relatively accurate, and has a mass of only 7 g.

The plane also has a 3-axis accelerometer (ADXL330) and two 2-axis rate gyroscope (IDG300) onboard. These sensors are not used for control, but are useful to measure the motion of the airplane for analysis, as shown in figure 9. The accelerometer measurements are first combined with the rate gyro by using a second order complementary filter:

$$\theta_{\text{comp}} = \frac{(\tau s+1)^2}{(\tau s+1)^2}\theta = \frac{\tau s}{(\tau s+1)^2}\dot{\theta}_{\text{rate gyro}} + \frac{2\tau s+1}{(\tau s+1)^2}\theta_{\text{gravity}} \qquad (10)$$

This filter combines the pitch measurement from the low frequency signal from the accelerometer (gravity measurement) with the high frequency rate gyro measurement to create a signal that doesn't drift, is immune to other acceleration than gravity and responds to fast change. The frequency at which the transition occurs is chosen by the parameter τ and has been experimentally chosen to be 0.1. Finally, using the pitch angle, the measurement from the

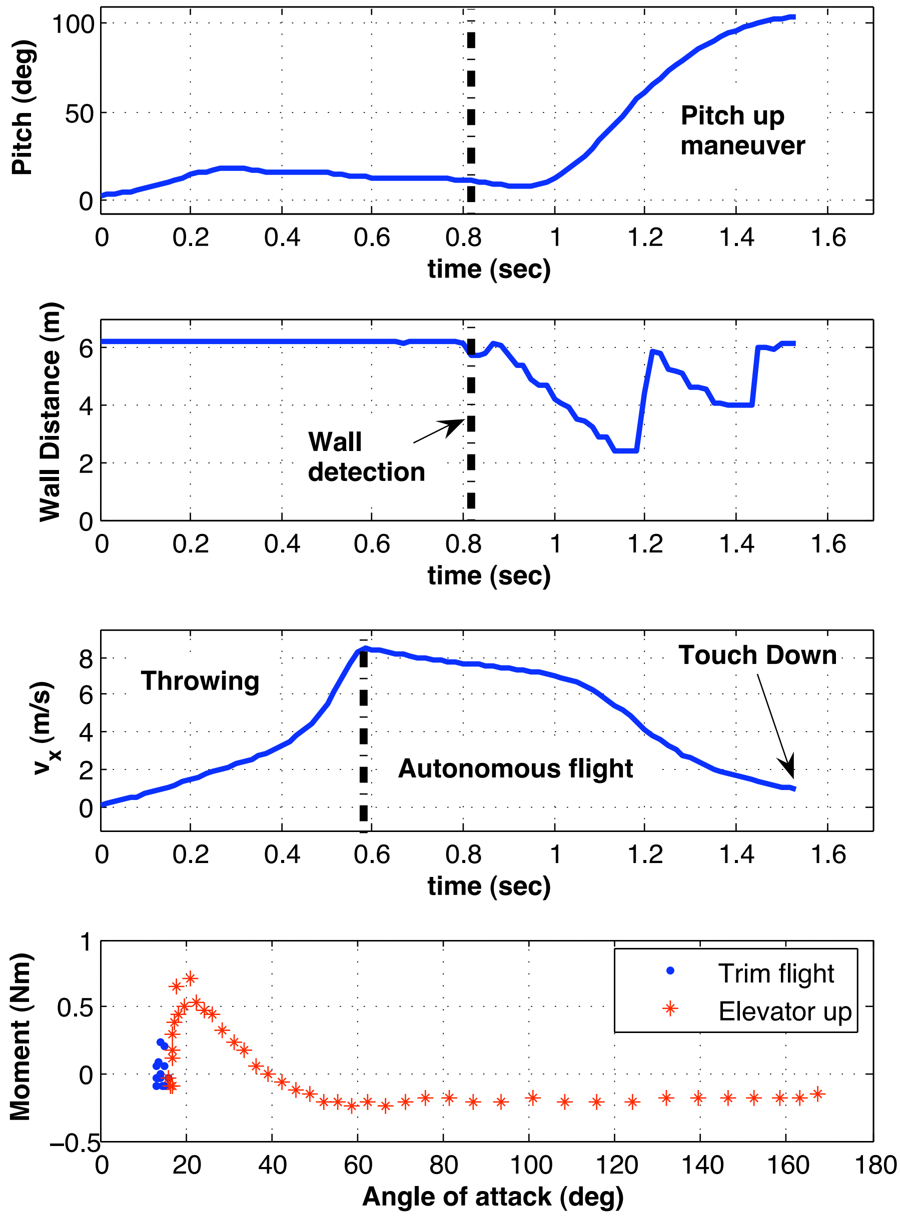

Fig. 9 Data collected during autonomous perching. The plane is released at 0.58 sec, glides toward the wall, detects the wall at 0.82 sec (6 m away from the wall) and starts pitching up. Pass 50 degrees, the plane rapidly slow down both its x velocity and its pitch rate. It then touch the wall at an pitch angle of 105 deg and a x velocity of 1 m/s. Some ripples are present in the wall distance sensor, thus the importance of having a robust maneuver and suspension. The pitching moment curve shows the trim flight condition (in blue), the high pitching moment created by the elevator up (red curve from 15-40 degrees) and the small negative moment that reduce the pitch rate to zero at about 90 degrees.

accelerometer can be integrated to get the x and y velocities. Examples of these measurements can be seen in figure 9

7 Results and Future Work

The early result reported in this paper is an integrated system. The non-linear suspension made from slow-recovery urethane is lightweight and robust while minimizing the impact forces and providing the proper engaging motion for the spines. Most importantly, the suspension-spines combination allows for a wide envelope of incoming velocities and orientations at touchdown which can be easily reached by using the natural dynamics of the airplane. The high initial positive pitching moment created by the upward elevator command is balanced by the small negative recovery moment that maximizes the plane's time in a favorable landing attitude. A typical perching maneuver, from wall detection to touchdown, lasts less than one second and reduces the speed of the airplane from 9 m/s to less than 2 m/s at touchdown. Figure 9 shows data collected during an autonomous landing and figure 8 shows a frame capture of the landing.

With such a system, it is possible to perch both autonomously and manually. A human can quickly learn the timing of the maneuver and perch the airplane on a wall. Approximately 30 successful landings have been performed so far: 20 manually operated and 10 autonomously controlled. The success rate is approximately 80% and it is possible to achieve many successive landings without having to tune or repair the system. The main cause of failure is false wall detection from the sensor, causing an early pitch-up maneuver which results in the plane not reaching the wall. The current distance sensor is operating near its maximum range, and the maneuver needs to be started as soon as something is detected. It is thus difficult to apply any kind of filter to prevent false detection and increase robustness.

The second cause of failure is from the plane pitching up too late, thus hitting the wall at a pitch angle of less than 60 degrees and breaking the suspension. This failure mode has been observed during manual landing, but has never been observed with autonomous perching.

The resulting perching system consisting of the foam suspension, spines and ultrasonic sensor weighs only 28g, a small percentage of the 375g weight of the total airplane. With optimization of the spines and structure, we believe that the weight can be reduced to less than 20g.

8 Conclusions and Future Work

This paper presents the design of an integrated system allowing a small, fixed-wing plane to land and perch on vertical suraces. The motivations are to greatly increase mission life and provide the plane with a stable, secure location that is relatively free of debris. The ability to grip vertical surfaces relies upon arrays of compliant microspines, adapted from climbing robots. The particular requirements of the spines for reliably engaging and gripping a surface lead to corresponding requirements for the incoming velocity and orientation of the plane and, most importantly, to requirements for a suspension that will asorb energy, maintain a steady engagement force, and prevent bouncing.

We present the design of a nonlinear damped suspension that meets these requirements, allowing a very simple fixed-wing glider to land with a relatively high success rate. [1]

Immediate work on the perching system will include increasing the wall sensor robustness and optimizing the trajectory to perform the maneuver in a shorter distance and maximize the amount of time over which touchdown is possible. We also plan to study the effect of adding a propeller and performing the perching maneuver when subjected to sidewinds.

Looking further ahead, a number of extensions are desirable to convert this technology into a practical solution for small UAVs. First, as soon as the plane comes to rest, it is desirable to engage a second set of spines that pulls upward, in opposition to the first set. By increasing the internal force between these opposed sets of spines, it becomes possible to sustain a much larger normal force due, for example, to gusts of wind. In preliminary tests, forces of several Newtons in the normal direction have been achieved.

The strategy of landing on buildings can also be extended to perching on other vertical surfaces such as tree trunks, which are actually easier to grip but much less regular, requiring a greater suspension travel. Another interesting possibility is to use directional dry adhesives, as used in gecko-inspired climbing robots [11] for climbing surfaces such as glass and smooth panels. The dry adhesives are conceptually similar to spines, but have narrower tolerances in terms of the required approach velocity and loading strategy; consequently they will require a more exact suspension design and more attention in controlling the approach velocity of the plane.

Finally, we need to address the ability to resume flight. One solution may be to use a small actuator to store elastic energy in the suspension "legs" and jump off the wall in a flight that is initially inverted, rolling to an upright position once away from the wall.

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[1] A version of the same spined toes and leg suspension has also been taken to MIT and retrofitted to the planes reported in [5], with similar results.

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