Bio-Inspired Perching and Crawling Air Vehicles

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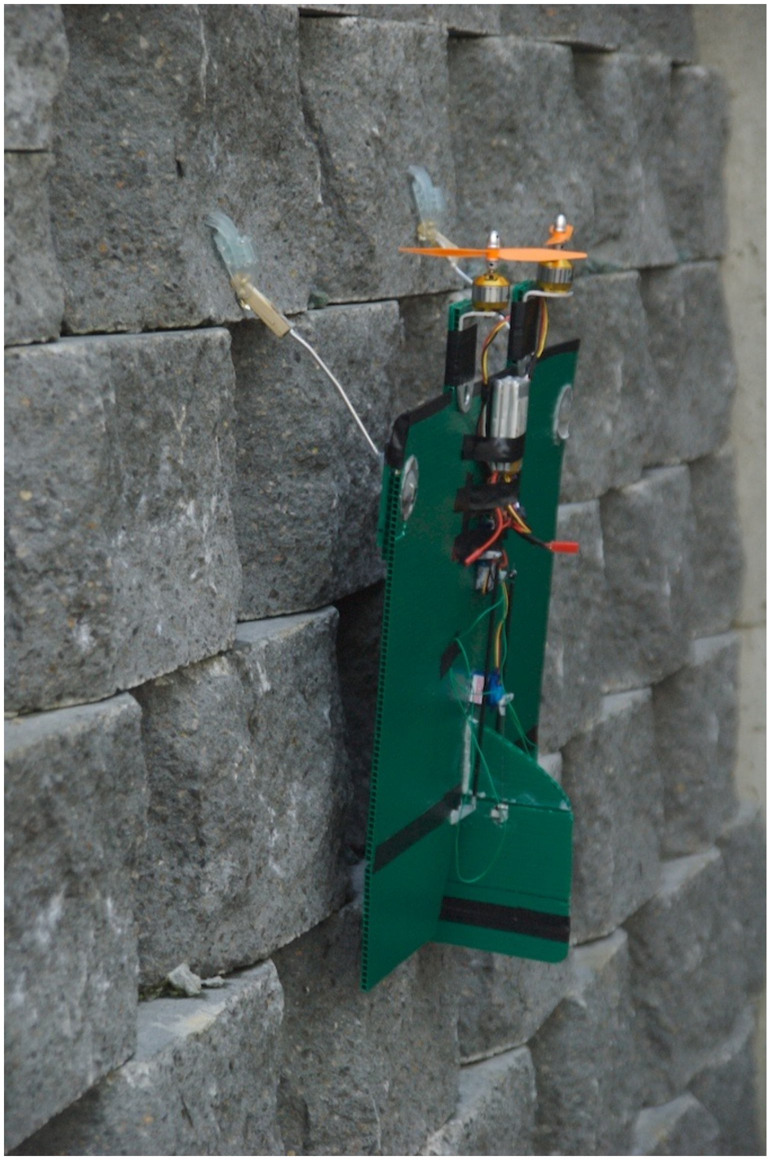

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A flock of small, unmanned air vehicles flies quietly into a city, maneuvering among the buildings. They communicate about their surroundings as they search for places to land, not on streets or rooftops but on the sides of buildings and under the eaves, where they can cling, bat or insect-like, in relative safety and obscurity. Upon identifying landing sites, each flier turns toward a wall, executes an intentional stall and, as it begins to fall, attaches itself to the surface with legs and feet equipped with miniature spines that engage the small asperities on the surface. Using its propeller in combination with its limbs, the flier can creep along the wall and reorient itself for a better view. By deploying actively opposed pairs of spines, the flier can cling tenaciously, to resist gusts of wind and ride out inclement weather. The fliers stay attached to the walls for hours or days, consuming little power and emitting no sound as they monitor the area. When finished, they launch themselves off the wall with a jump and become airborne again, ready for their next mission.

1 Introduction

While the foregoing scenario may sound like science fiction to the lay reader, essential pieces of the underlying technologies to support this scenario are in place. Those technologies, with the research outlined in this white paper, can be extended and integrated to make the scenario a reality and allow small airplanes to *identify* suitable locations, *execute* controlled, low-speed landing maneuvers on arbitrary surfaces, *cling* and *crawl* to save power while conducting surveillance, and *jump* to regain airborne mobility.

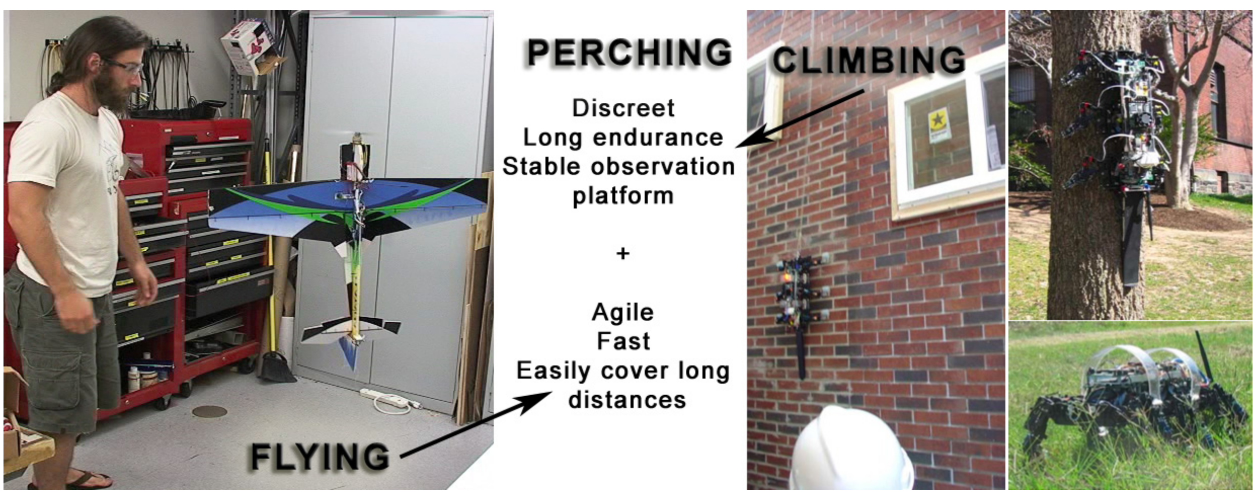

Figure 1: Left: a hovering airplane at Stanford BDML using a modified version of the Paparazzi controller [26]. Right: RiSE climbing platform on various surfaces. Perching MAVs combine some of the best features of both technologies.

We propose a plan of research in micro-air vehicles (MAVs) and bio-inspired robotics to (i) investigate the details of landing, perching and take-off from arbitrary vertical surfaces in small animals including birds, bats, spiders and flying lizards (ii) identify strategies for adaptation to bio-inspired robotic platforms and (iii) demonstrate the validity of the identified principles through a series of increasingly challenging applications scenarios.

The work builds on recent accomplishments in the control of autonomous low speed maneuvers for MAVs and in the design and control of robots that climb and maneuver on vertical surfaces. It confers large practical advantages over either of these capabilities in isolation, providing a solution with the speed and versatility of a flier and the extended mission life, stealth and tenacity of a climber. Table 1 summarizes how this approach addresses major limitations of current MAVs.

Table 1: Limitations of MAVs and advantages of a hybrid flying/perching/crawling platform.

Limitations of current MAVs	**Hybrid platform advantages**
Short mission life, especially if using electric power.	Long missions due to low energy consumption while perched. Possibility of solar charging.
Small MAVs have fast dynamics that complicate video and ranging surveillance.	Clinging MAV is a stable observation platform. It can also crawl to reorient as desired.
Fragile MAVs that land on the ground are vulnerable to accidental or malicious damage.	MAVs clinging high above the ground are out of harms way.
Ground may be cluttered with debris, making it hard to find space for landing and takeoff.	Walls remain relatively free of debris. Spines are not affected by film of dirt or moisture.
MAVs that land on horizontal surfaces are vulnerable to gusts of wind and inclement weather.	MAVs that cling to building walls can resist wind gusts. If perched under overhangs, they can ride out inclement weather.
MAVs are expending energy and making noise while moving.	Perched MAVs can be stationary and quiet, producing minimal detectable emissions.
Perching on a wire or pole: Detection of a wire or pole for autonomous perching is difficult. Wires are flexible and do not provide a stable observation platform.	Walls are easy to detect and provide a stable observation platform. They are also common in an urban environment.
Autonomous take-off usually requires a runway and consumes significant energy.	Jump-assisted take-off from a wall lets the plane reach airspeed quickly while clearing obstacles.

2 Background and related work

The scenario given in the introduction requires capabilities that no current ground or air vehicle can achieve. This section summarizes the current state of the art in acrobatic MAVs and climbing robots and describes new challenges arising from perching.

Unmanned Air Vehicles

Unmanned Air Vehicles (UAVs) have been the subject of extensive research and development. Commercial systems like the Aerovironment Dragon Eye [2], Raven B [3] and the smaller WASP III [4] are designed to suit a wide range of missions. The Black Widow [18] was an early Micro Air Vehicle (MAV) specially designed for endurance. Although smaller MAV and flapping wing vehicles are still the subject of research, a few interesting prototypes already exist including the DelFly II [14] and the University of Florida Gator A [30]. Table 2 summarizes the specifications of these systems.

Table 2: Review of a few different UAV systems [14, 18, 30, 4, 3, 16, 2].

Airplane	Endurance	Range	Speed	Wing Span	Weight	Type
DelFly Micro	3 min	50m	NA	10cm	3 g	Flapping wing
DelFly II	8-15 min	NA	-0.5 to 15 m/s	30cm	16 g	Flapping wing
Black Widow	30 min	2km	30 mph	6 in	100 g	Airplane
UofF Gator A	20 min	10 mile	35 mph	12-16 in	150g	Flexible wing
WASP-III	45 min	5 km	40-65 km/h	72 cm	430 g	Airplane
Draganflyer X6	25 min	NA	0-50 km/h	99 cm diam.	1 kg	Quadrotor
Raven B	60-111 min	10 km	20-57 km/h	1.4 m	1.9 kg	Airplane
Dragon Eye	45-60 min	5 km	35 km/h	1.1 m	2.7 kg	Airplane

From table 2 it is immediately clear that mission life decreases with UAV size, due to reductions in efficiency and the difficulty of providing a high-energy density source in a small volume. In particular, flapping-wing and rotary aircraft are generally much less efficient than a fixed-wing platform. Rotorcraft had historically the advantage of hovering, but some fixed-wing planes are now capable of aerobatic maneuvers including autonomous hovering and flying inside a building [17, 19].

Perching has been studied mostly from the aerodynamics point of view. For example, researchers at MIT [17] have been using a 119Hz Vicon motion capture cameras to track plane position to sub-millimeter accuracy. This positioning system is then used to control the plane, with computing done off-board for various indoor maneuvers such as take-off, hovering, flying in a room and perching. Another group [13] has recently been able to use the same motion capture system to create an accurate high-dimensional model of a glider during high angle-of-attack (AOA) maneuvers. This allows them to perform aggressive maneuvers required to decelerate the glider 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 is successful approximately 20% of the time.

With proper sensing, simple maneuvers can be performed using onboard electronics. As an example, Drexel University have a fixed-wing aircraft capable of hovering [20, 21, 19]. This airplane has a controller based on the PIC16F87 and uses a Microstrain 3DM-GX1 inertial measuring unit (30 grams, 100 Hz update rate) to measure its spatial orientation. The plane uses rudder and elevator to control pitch and yaw and has small propellers on the wing tips to control for roll. At the Stanford BDML, similar hovering is achieved using an open-source autopilot [26] without extra propellors on the wingtips (Figure 1). Details of the Stanford BDML controller are included in Appendix A.

Other research at Cornell University [33, 31, 32] has focused on performing the perching maneuver using a morphing airplane. They simulate an aircraft that pitches up its body to slow down before perching but keeps its wing and tail horizontal so that it remains in control and still creates some lift during the entire maneuver. This approach creates a shorter perching trajectory than one would usually get with a rigid airplane, but adds mechanical complexity.

Until recently, and because of their particular needs, most UAVs have used proprietary autopilots. Over the last few years a team at ENAC University have developed the open-source Paparazzi autopilot [26]. This autopilot is able to perform most maneuvers required for regular flight (fly-by-wire, take off, climb, level flight, waypoint navigation and landing) using only GPS and IR sensors, and can be easily modified to perform other maneuvers with additional sensors. It has been tested on a variety of platforms and includes a ground station and simulation package. The basic configuration uses a LPC2148 MCU, controls up to 8 servos and integrates the GPS in a package weighing 24g.

Climbing & Jumping Robots

Robots like RiSE and Spinybot [5, 29] have demonstrated the ability to climb reliably on a range of typical building surfaces including brick, stucco, concrete and wood. These robots use arrays of small (10-25 micrometer tip radius) spines that hang on asperities (small bumps or pits) on the surface. Each spine is supported by a nonlinear suspension that increases the probability that the spine will engage an asperity as it is dragged a short distance along the wall. Collectively, the suspensions also distribute the load among many spines, as each spine can only support a small force. Examples of spines and a diagram of spine/asperity contact are shown in Figure 2. Working in tandem with the suspensions, the robot leg trajectory is controlled to facilitate spine attachment and detachment at the beginning and end of each step. The robot also applies internal lateral forces, tangential to the wall, that allow the spines to provide a greater pull-in force on overhanging surfaces. In comparison to other wall-climbing technologies such as suction or vortex [23], magnets, and pressure sensitive adhesives, spines have several advantages: they require no power for clinging, they work on a wide range of outdoor surfaces and are relatively unaffected by films of dirt and moisture, they can support large loads, and they leave no trace of their passage. Climbing robots, however, are relatively slow, and transporting them to the site of interest can be a challenge.

Recent research on small mobile robots has also explored jumping, inspired by the ability of insects and small rodents to surmount large obstacles by storing energy and releasing it with a large jump [28]. A recent example from EPFL weighs 7 g, is 5 cm tall and can jump over obstacles 27 times its own size [25]. Stabilization of the jump remains an open problem. Current research is focused on using small airfoils that are deployed shortly after take-off to help stabilize the jumper in flight.

In another preliminary demonstration of hybrid air and ground mobility, some legs inspired by the Whegs vehicle from CWRU were added to a MAV from the University of Florida for landing and take-off [6]. Stability for landing remains a challenge and, in this approach, the weight and drag from the wheel-legs interfere with flying. For successful take-off, the platform requires launching the robot from approximately 20 feet above the ground.

Bio-Inspiration

Extensive biological research has been devoted both to flying and to ground locomotion. However, little research has focused on the physics of the transitions that occur during perching and take-off. In this section we do not attempt a thorough review, but list a few intriguing discoveries that may provide clues for a hybrid perching air vehicle.

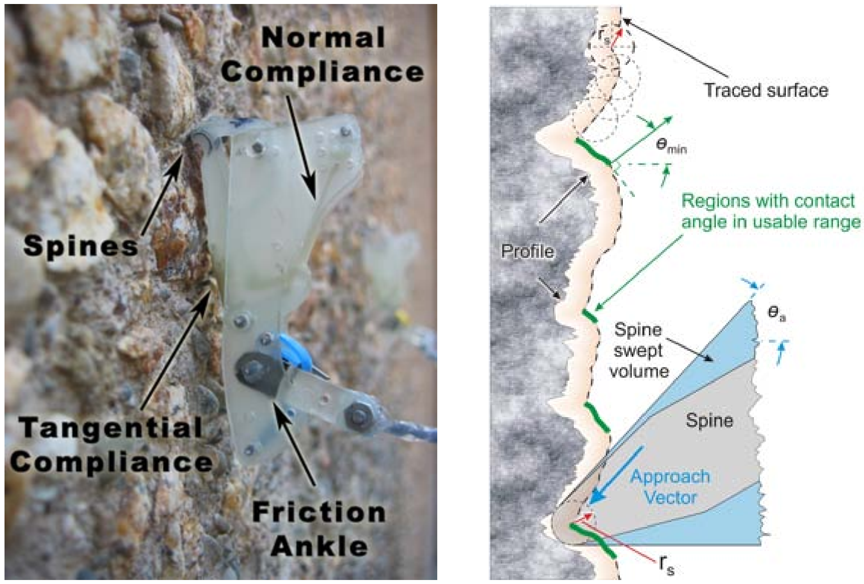

Figure 2: Left figure shows the new foot designed for perching. Notice the black area, made of sorbothane, at the ankle to increase the damping. The right figure shows the traced surface created when dragging a spine over a surface (concrete profile shown). Perchable regions are shown in bold and depend on friction and spine geometry.

It has been suggested that flying evolved from the advantages of having small lifting surfaces [9] on running and jumping animals. Studies show that only a small amount of lift is required for control during jumping and to reduce landing forces. The flying squirrel is one example of an animal that has evolved to control landing forces. Its low aspect ratio wing provides aerodynamic stability and creates lift at angles of attack up to 40 degrees without stalling. 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 [27, 8].

Legs and wings are used in combination in many bird and insect species. Birds able to take-off vertically can produce up to 2G of acceleration with their legs before they start flapping their wings [22]. This creates an initial velocity and helps them to clear obstacles that could impede wing motion. At a much smaller scale, the fruit fly also uses a combination of wing thrust and stored energy in the legs. Voluntary take-offs make greater use of the wings for control, but escape take-offs use the legs, with the wings held close to the body to achieve maximum jump height before switching to flight [10]. Some birds also use their wings for assistance in climbing, during which time they beat with a different stroke that provides a positive normal force against the wall, thus improving leg traction [7, 15].

3 Proposed research

The proposed project goal is to create a system that will allow a small fixed-wing airplane to perch autonomously on a variety of vertical surfaces for extended periods of time, crawl on the surface to reorient itself and take-off with the help of jumping. For the work in this section, we focus on a fixed-wing platform weighing approximately 500 grams. Significantly larger and heavier planes (e.g. Raven B in Table 1) can generally be designed to have greater endurance and are less suitable for the maneuvers required for perching on arbitrary surfaces. Rotorcraft are capable of hovering and performing dramatic maneuvers [12] but are comparatively noisy, slow and inefficient. In addition, landing, perching and crawling with rotorcraft may be no easier than with a fixed-wing plane.

The proposed system will comprise a controller, an active suspension system and a sensor suite. Although it is initially focused on small fixed-wing MAVs, many of the underlying results can be transfered to other platforms (e.g. with deformable wings) in the second phase. In the following sections we first summarize some of the key research challenges and questions that arise. We then propose a plan of research that will take planes through the various stages of approach, landing and take-off.

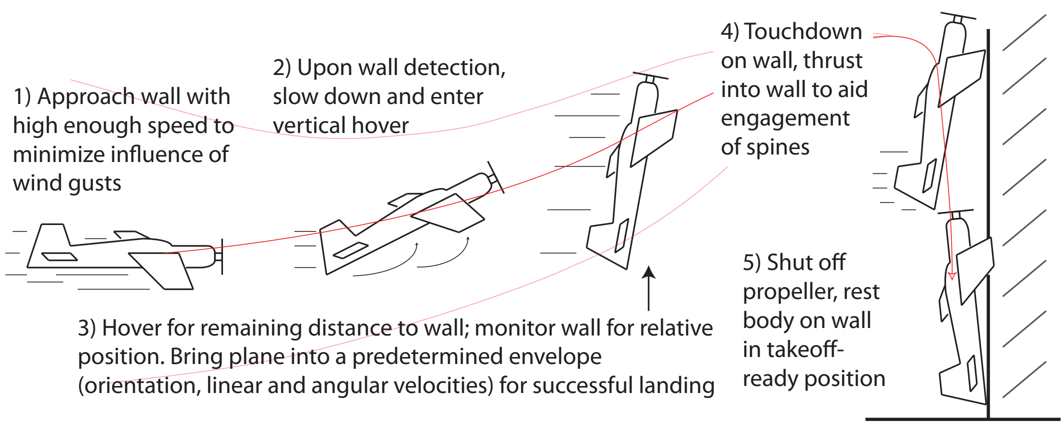

Figure 3: Landing sequence for perching on a wall.

3.1 Research challenges and questions

Much of the difficulty associated with landing and perching arises from the need to accomplish these maneuvers robustly, in an outdoor environment, and on a small autonomous platform. Research questions arise in the areas of controls, sensing and signal processing, actuators, motion planning and bio-inspired mechanisms:

- **Intelligent control:** How can previous work on acrobatic maneuvers and learning algorithms be adapted to a self-contained platform? For example, can we simplify the machine learning techniques employed for system identification and control by [13] or [12] for use on a fully contained aircraft with a modest weight budget for onboard sensors and processing? Is it possible, considering that the perching maneuvers only last 2-3 seconds, to reproduce the results with only GPS, accelerometer and gyroscope? Can we draw insights from the approaches taken by insects to achieve reliable landings using a small brain, well adapted passive mechanisms and integrated sensing?

- **Sensing:** What sensors will provide the most reliable information regarding wall detection, and plane velocity and attitude with respect to the wall before and after contact? Can we filter the noisy information to improve our knowledge of the system quickly enough to provide useful closed-loop corrections during landing? Will the sensors be sufficiently compact and robust? To what extent can the legs and toes provide tactile sensing to improve knowledge about the state of the plane and the characteristics of the wall?

- **Legs and suspension:** What are the optimal properties for the suspension system? What is the best way to extract energy from the plane so that it can land gently? How can we create a suspension that will favor spine engagement for a range of incoming velocities and orientations? Can we obtain sufficient controllability using only semi-active elements (e.g. controlled brakes) that dissipate large amounts of energy for their size and weight?

- **Crawling:** How can we control the plane using a combination of vectored thrust from the propellor and flaps, and actuation of the legs and toes, to move in a desired direction on the wall? Will the planned maneuvers work on rough walls, when contact is intermittent?

- **Gripping:** How much gripping force must be generated to resist wing gusts? What is the best way to detect when a grip is failing so that the plane can recover before it falls?

- **Jumping:** How should jumping be integrated with the return to flight? How can the control surfaces of the plane be used to help stabilize the jump? How can the take-off approach be extended to MAVs with a thrust to weight ratio smaller than one?

- **Ground effects:** Can the changes in aerodynamics as the plane approaches a large wall be used to facilitate landing? Are there specific lessons to be learned from animals such as flying squirrels and bats about exploiting ground effects on vertical surfaces?

- **Platform design:** What modifications can be made to the plane to provide more controllability during landing and take-off, and to increase the robustness of the plane, without impairing its flight performance?

3.2 The process of approaching, landing, gripping and take off

Figure 3 illustrates the sequence of actions required to perch on a wall with a fixed-wing plane. Initially, the plane approaches the wall at cruise speed. Upon wall detection (5 to 10m away), the plane pitches to slow down and stays in that orientation until wall contact. The suspension then absorbs most of the impact in a way that allows the spines, or other adhesive technologies, to engage the surface. To further enhance the probability of spine engagement, some control is applied during the short landing phase (e.g., by keeping the thrust oriented toward the wall) before complete rest. Once landed, the plane can reorient itself, remain still for extended periods of time, or take-off as desired. The following section describes some of the core activities associated with each stage of the process.

In parallel, investigations into biological exemplars will provide inspiration for design and control principles. Previous research has shown that much can be learned from joint biological and robotics investigations to develop robots that run faster [11] or climb a range of surfaces using technologies like spines and dry adhesives [29, 5]. Similar results are expected from the investigations of landing, perching and controlled jumping in spiders, flying lizards and birds. These insights will inform the development of new MAVs, which will be inherently better suited to the requirements of frequent landing, perching, jumping and take-off.

To frame the discussion, we embed a cartesian coordinate frame (x_s, y_s, z_s), as shown in Figure 4, at the spines, which are generally arranged in a short row on the tip of a toe. When the toes are properly aligned for gripping, the direction x_s points upward along the wall, in the opposite direction of gravity, and z_s is normal to the wall.

Stage 1 - Initial approach

The first stage encompasses steps 2-4 in the sequence in Figure 3. As the plane approaches the wall, the parameters of interest include its distance to the wall, x_f, its linear and angular velocity $[v_{x_f}, v_{y_f}, v_{z_f}, \omega_{x_f}, \omega_{y_f}, \omega_{z_f}]^T$ and its orientation defined by bank, elevation and heading angles, $[\phi, \theta, \psi]^T$. Our emphasis is particularly on the final tens of centimeters of flight before contact, when there is little time for closed-loop control to modify the state variables; consequently, the final maneuver will be largely open-loop. The goal is primarily to bring the plane's final touchdown velocity, and bank and elevation angles, assuming small heading change, within an envelope $E(\phi, \theta, v_{x_f}, v_{z_f}, \omega_{x_f}, \omega_{y_f}, \omega_{z_f})$ in the instants before touchdown such that the next stage can proceed.

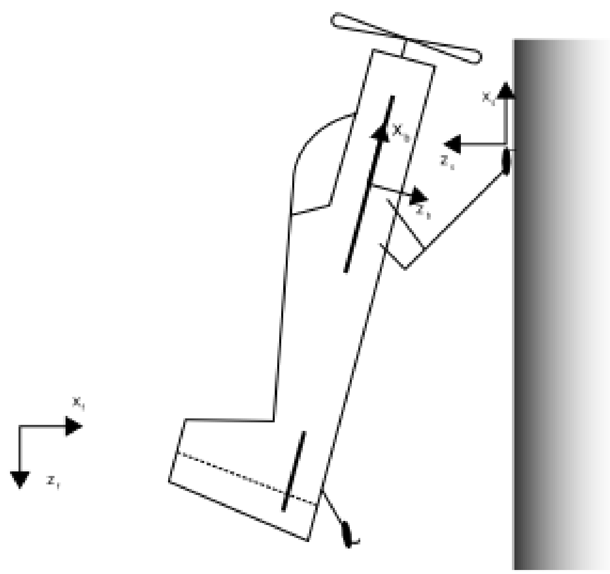

Figure 4: Plane on a wall and reference frames.

The maneuver is accomplished using only the propeller and control surfaces. Initially, to maximize control authority, the MAV will be taken from the class of lightweight acrobatic planes that can hover for short periods of time (such as the plane in Figure 1). Subsequent work will expand the approach to MAVs such as the Wasp-III [4] that cannot hover and have minimum flight speeds above 3m/s. In this case, the plane must execute an intentional stall just prior to contacting the wall. The methods used in [13] for perching a glider on a bar or wire may be applicable. However, an interesting feature of landing on an extended wall is that ground effects become important and can help with stabilization. MAVs with deformable wings represent another interesting opportunity for exploring approaches like those taken by birds, flying squirrels and bats to shed velocity rapidly in the final stages of flight [27].

For the proposed work, a controller derived from the open-source Paparazzi Autopilot Project will be refined and used to experiment with different landing trajectories for spine engagement. The development of entirely new MAVs and controllers is not initially a focus of the proposed work. We have established that the Classic board from Paparazzi for a vehicle such as the Flatana 3D aerobatic plane can be adapted for our purposes. We have implanted a new controller on this board, using a lightweight IMU and ultrasonic range sensor, to achieve controlled hovering and transitions between flight and hovering in large indoor spaces. Although hovering has been accomplish with the IMU, the current algorithm combining the measurements is designed only for small rotations. A more general filter is under development and will combine the information from GPS, accelerometers and rate gyroscopes to get a more accurate state estimation during 3D maneuvers [24].

This sensors suite will then allow us to improve our plane's model so that we can simulate, optimize [12] and implement specialized maneuvers for smooth landing and take off. The model will be created using a technique from [13, 1] adapted to onboard sensing. This approach consists in performing numerous trajectories, similar to the desired task, and fitting a model that will minimize the prediction error given the current state and action.

As the plane approaches a wall or other surface, absolute sensing of velocity and orientation with respect to the surface becomes possible. Candidate sensors include ultrasonic and optical (imaging, flow or triangulation based) sensors, chosen for low weight, robustness, and the ability to produce information that is not too noisy. Tests will be conducted to determine which combination of sensors is most effective. It is interesting at this stage to investigate how animals, but mostly insects because of their limited sensing and intelligence, detect the wall and prepare themselves for landing.

In Phase II of the proposed work, we will investigate the use of deformable wings for increased durability from the impact, better aerodynamics during high angle of attack maneuvers and better exploitation of ground effects to help in slowing down the plane.

Stage 2 - Stabilization and spine/asperity contact

After initial contact, the degrees of freedom of the plane are successively reduced as one and then both feet are brought into contact. Passive and active properties of the legs are now available for stabilizing the plane. The goal is to enter a smooth trajectory that lightly drags the spines down the wall to facilitate engagement while maintaining a small force normal to the wall. Our initial approach is to rely primarily on passive compliance in the legs, based on previous success with under-actuated leg mechanisms in Spinybot [5]. The suspension needs to be designed to provide the desired force and motion trajectory. On surfaces with smaller asperities, the thrust vector can be oriented slightly toward the wall to provide more normal force and increase the likelihood of the spines grasping an asperity (Figure 2).

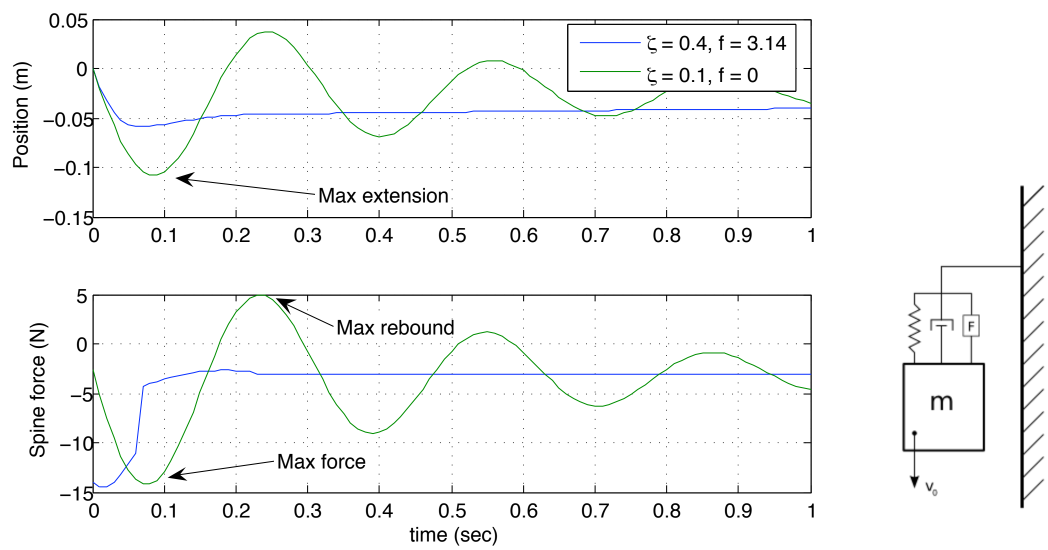

Figure 5: Comparison of conventional lightly-damped suspension and nonlinear hysteretic and friction damping suspension. The nonlinear suspension eliminates the rebound which would make the spines release and reduces the maximum force.

The role of the suspention is to favor engagement of the spines, in the presence of uncertainties. To do so, the suspension must absorb the landing impact without creating any rebound, while also minimizing the required suspension travel and the forces transmitted to the airplane. In preliminary work, we have developed a nonlinear passive leg suspension (shown in the photograph in Figure 2 and modeled in Figure 5), that uses a combination of friction and hysteretic damping to prevent any rebound in the force loading the spines. This is important because the spines can resist normal forces as long as they are loaded in shear. Assuming the plane is moving downward, dragging its spines on the wall, the nonlinear suspension is much better at ensuring successful spine loading. The next step is to extend the analysis to a multi-degree of freedom problem involving loading in all three directions. Particular attention will be paid to mechanisms used by animals during perching on vertical surfaces and the roles of tendons, muscles and skeleton for stabilization, force dissipation and spine or claw engagement.

In parallel with numerical modeling of active and passive leg mechanisms it is important to conduct tests of landing trajectories. Unfortunately, running many landing tests will initially result in many crashes, requiring repairs to the plane. A more efficient solution for exploring the envelope of possible initial conditions is to use a high speed robot arm to repeatedly launch an inexpensive, crashworthy airplane proxy, equipped with legs, toes and spines, toward the wall. For this purpose, we can use the Adept One MV robot at Stanford. This robot is capable of tip speeds up to 9m/s, which is more than adequate for testing our landing strategies and starting to establish the “envelope” of feasible orientations and velocities from which attachment can proceed. In Figure 6, the Adept grasps the plane and brings it to a specified orientation and velocity with respect to wall before releasing the plane, which then travels without active control until it grasps the wall surface.

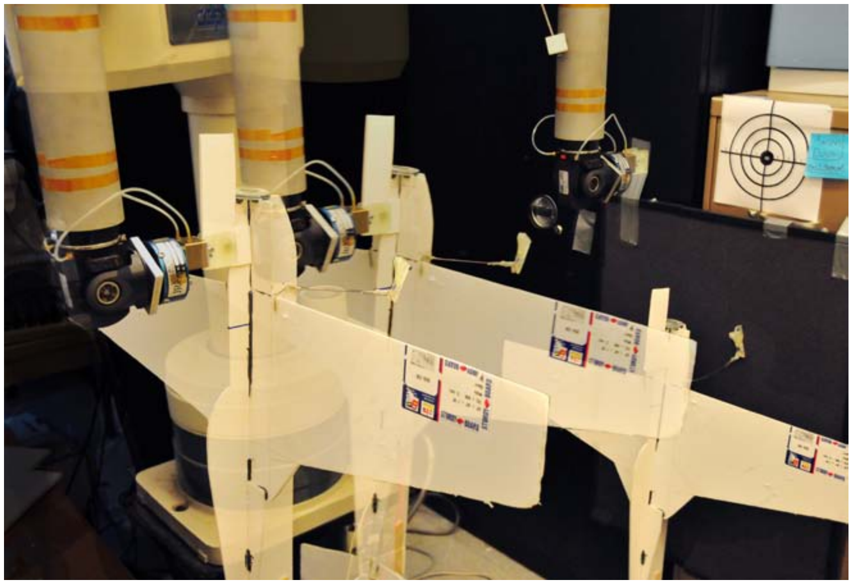

Figure 6: Sequence of images of the Adept robotic arm being used to throw the plane on a specific trajectory.

One of the challenges in designing the leg suspension is that traditional shock absorbers and actuators are undesirably heavy. The leg will therefore need to exploit nonlinear viscoelastic materials and friction brakes, etc. Our lab has designed prototypes of small and lightweight mechanically-tuned systems composed of different materials using Shape Deposition Manufacturing [11, 5]. In early experiments, we have used the Adept robot to test the suspension, at various speeds and trajectories, on an un-powered plane to help us develop designs that we can compare with simple numerical models.

Figure 7 shows a comparison of experimental and actual forces and velocities for two different designs. *Suspension 2* is an improved version of *Suspension 1*, with greater damping due to nonlinear friction elements. This suspension, although still not optimized, performs significantly better, allowing the airplane to land with initial velocities as high as 2.5 m/s.

Stage 3 - Spine loading and gripping

At the start of the final stage, the spines are traveling along the wall. We know from prior work [5, 29] that the ability of spines to engage asperities on a surface is a function of several factors, particularly spine tip radius compared to average asperity size, surface roughness properties including the average amplitude, narrowness and slant of peaks and valleys, number of spines per foot and the spine approach vector, which creates a swept volume that interacts with the surface. The general problem is captured in Figure 2, which shows a spine creating a traced surface as it slides along a concrete profile. The marked regions are those on which the spine can perch. Spine and asperity strength both scale as L^2, however, the probability of finding an asperity large enough to perch on scales roughly as $1/L^2$ for many surfaces such as concrete and stone,

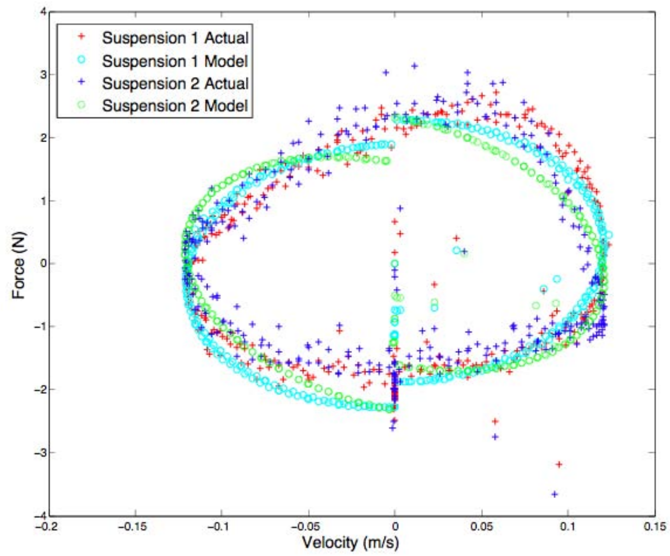

Figure 7: Testing of two different suspensions. Suspension 1 has a damping ratio of 0.02 and fails if the vertical (downward) velocity at landing is higher than 0.8 m/s. Suspension 2 has a higher damping ratio (0.23) and gives the plane a larger envelope of initial conditions, with vertical velocities up to 2.5 m/s.

which have a fractal surface characteristic over some range of length scales. Practically speaking, for spines with a tip radius of 10 μm or greater, surfaces equivalent to 120 grit sandpaper or rougher will present enough asperities per unit area for reliable gripping.

Spines can sustain loads of approximately 3.5N on surfaces like sandstone or concrete. Thus for the current plane (350 grams), only a few spines are needed on each toe. A total of 10 spines is currently used to absorb the dynamic load of landing (5 grams per foot, without any weight optimization), usually 2-10 times higher than the static weight of the plane depending on the touchdown velocity and suspension design. On friable surfaces like adobe, more spines may be needed to avoid failure of the surface asperities.

The spines are supported by a compliant suspension in the toe, whose stiffness can be defined at any instant with a configuration-dependent stiffness matrix, K. The design of multimaterial elastic toe mechanisms will build upon previous work for Spinybot, RiSE and Zman [5, 29]. In the present case, the parameters of the stiffness matrix should be such that initially the stiffness in the Z direction is very low (to prevent bouncing) and the off-diagonal terms K_{xz}, $K_{x\theta}$, $K_{z\theta}$ should be low to prevent rotation of the spine, which could cause it to slip off an asperity.

Because spines are directional, they only engage asperities and resist combinations of tangential and normal force from a single direction. For a climbing robot, the weight of the robot is sufficient to load the spines, but for a MAV, especially in windy weather, we cannot rely on gravity. The solution is to use opposed pairs of spines. Rough prototypes have resisted pull-off forces as large as 10 N (Figure 8). Improved versions will use actuators for automatic deployment. Opposition can occur within a foot, with toes having opposing spine directions, or between feet, using one or more actuated feet near the tail of the airplane.

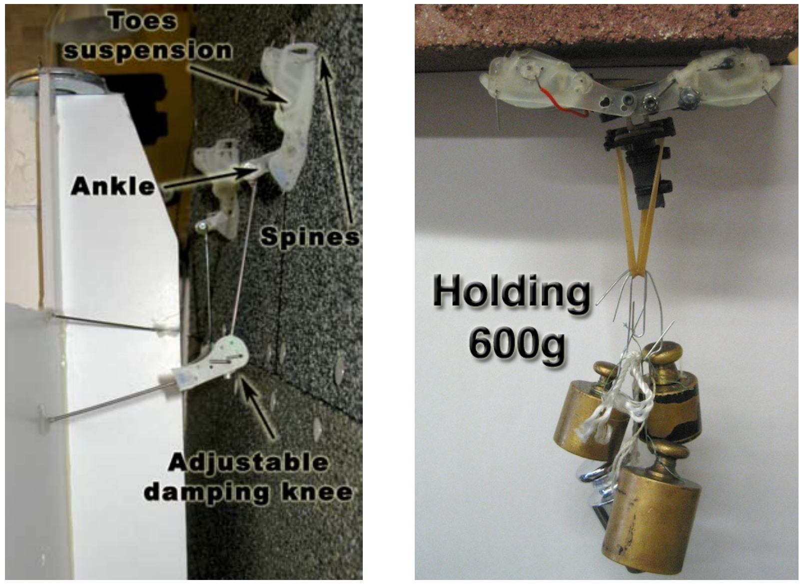

Figure 8: The figure on the left shows an unpowered replica of the plane clinging to a wall with compliant legs. This linkage allows impact absorption at the ankle and knee joints, while favoring spine engagement. The knee and ankle provide a combination of stiffness, damping and friction. The figure on the right shows an early prototype of opposing spines passively holding 600g.

Wall maneuvers and take-off

During Phase II of the proposed work we will explore strategies for using a combination of propeller power and legs with spines to execute maneuvers on the wall. The first of these maneuvers is crawling forward, inspired by wing-assisted climbing [7, 15] in a few bird species, and can be achieved using the propeller and the plane control surfaces to guide the legs. Note that with spines in contact, each foot can slide forward but not backward. Using this crawling motion, the plane can be slowly reoriented to get a better observation angle or reach a more secure location.

Another maneuver that could benefit from interaction with the wall is to do a jump assisted take-off. This would allow the plane to reach airspeed almost immediately after it disengages its spines and to clear the wall with minimum altitude lost. Such maneuvers would be especially useful on planes with a thrust to weight ratio less than unity. The mechanism for storing elastic energy and releasing it can be adapted from other recently developed small jumping robots [25]. We will also investigate whether the elastic and damping mechanisms that stabilize the plane during landing could be effective during takeoff as well.

While not related to perching, that jump assisted take-off ability could be useful on the ground as well. Most MAVs are so light than they can land successfully and robustly by doing a simple "crash" onto the ground. But take-off remains a problem, especially on uneven terrain. A jump-assisted take-off could overcome this problem.

Summary

In summary, the process of landing and perching can be decomposed into a series of clearly defined stages that make it feasible for a small plane to execute the entire sequence autonomously. The main challenge will be to do it reliably, in the presence of sensor noise, wind gusts, etc. Much of the proposed work is aimed at developing robust solutions for mechanisms, sensor interpretation and control that will provide reliable operation under realistic conditions.

Table 3: Summary of proposed tasks, milestones and timeline

Basic landing, perching, take-off from vertical surfaces.	**Option 1: Advanced sensing, communications for applications & technology integration in a new aircraft.**	**Option 2: Bio-inspired maneuvers and mechanisms for greater agility, versatility, reliability.**
Phase I (12 months) Numerical models and tests (Figure 7) to develop deployable leg and toe suspension elements for spines that accommodate range of incoming orientations & velocities, absorb energy, prevent bouncing and promote spine engagement. Conduct tests on concrete, brick, stucco and adobe wall surfaces.	Develop robust, miniaturized integrated microprocessor, sensor and power system for the payload sensors.	Review biology literature and identify animals best suited for further investigation of landing, perching and take-off strategies.
Use Adept One robot (max speed 9m/s) (Figure 6) and vision tracking to establish envelope of initial orientations, velocities for successful landing maneuvers.	Integrate the payload sensors to the Paparazzi communications system for transmitting information to/from the MAV sensor suite.	Particular attention to mechanisms and behaviors used by bats or insects that regularly land and perch on vertical surfaces.
Extend the MAV attitude and position estimation to 3D maneuvers. Add sensors to use absolute (ultrasonic and/or laser) sensing of orientation & velocity with respect to the wall. Test different combinations of sensors and signal processing methods for best accuracy and reliability across a range of wall surfaces.	Determine the suite of sensors to pursue for applications (e.g. surveillance, environmental monitoring or surface characterization).	Explore take off strategies for rapidly establishing airspeed.
Perform system identification on the plane. Extend controller to perform the optimal perching maneuver with a combination of feed-forward behaviors and closed loop control for improved low-speed control of attitude and orientation in the final 0.5m of flight.	Conduct tests of initial sensor suite, initially using MAV manually placed on the wall and subsequently using a MAV that lands autonomously.	Conduct 3D tracking and force plate analysis of landing for comparison with numerical results on MAV and leg suspension.
Develop a take-off maneuver that will rapidly transition the plane into the flying regime while allowing the spines to release from the wall.	Identify and test suitable MAV platforms for technology transition in Phase II.	Analyze the role of passive structural mechanics in stabilizing and absorbing energy.

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Basic landing, perching, take-off from vertical surfaces.	**Option 1: Advanced sensing, communications for applications & technology integration in a new aircraft.**	**Option 2: Bio-inspired maneuvers and mechanisms for greater agility, versatility, reliability.**
Conduct initial tests of the complete Phase I demonstration cycle: approach to wall, landing, perching, power off, clinging, power on, take off, return. Conduct tests of energy consumption at each phase.		Analyze claw geometry and grasping mechanics for perching.
6 month: Execute demonstration cycle with slow hovering approach. Tests will initially be conducted under supervisory RC control, with low-level stabilization from the MAV controller.		
12 month: Execute demonstration cycle with dynamic landing transition. Final demonstration (12 months) will be a fully autonomous demonstration of the cycle under calm conditions.		
Phase II (12-24 months) Develop mechanism for engaging secondary, opposed spines to achieve a high pull-off force for resisting winds and for hanging on inverted surfaces. Test the tenacity of clinging with opposed spines on various surfaces maximum force and maximum wind gusts.	Design of new MAV, or integrate perching technologies into an existing platform.	Conduct detailed micro and macro-scale analysis of the role of tendons, muscles, skeleton on stabilization and ensuring that claws are brought into favorable orientation on contact.
Develop mechanism and control strategy for jump-assisted takeoff to reach airspeed rapidly with low energy consumption.	Trajectory generation for planes with thrust to weight ratio smaller than unity.	Investigate jump-assisted take-off strategies from standpoint of energy storage and release and stabilization.
Robustness: Demonstrate autonomous approach, landing, perching, take-off in light winds. Develop safe recovery procedures for when spines fail to engage the surface.	Explore deformable wings for improved low-speed control and damage tolerance.	Investigate specific sensory responses and reflexes for landing, take-off that may be applicable to implementation on deformable-wing MAVs

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Basic landing, perching, take-off from vertical surfaces.	**Option 1: Advanced sensing, communications for applications & technology integration in a new aircraft.**	**Option 2: Bio-inspired maneuvers and mechanisms for greater agility, versatility, reliability.**
Develop mechanism and control for slow crawling and reorientation on wall surface.	Develop and test selected applications scenario (e.g. environmental monitoring, surveillance).	Investigate bird performing wing-assisted climbing.
Increase range of building surfaces that plane can perch on (e.g. wood, metal) and demonstrate graceful failure in the event that landing and perching is not possible (e.g. surface too smooth or winds to strong to permit attachment).		
Demonstration: For multiple building materials (brick, concrete, stucco, wood, metal) demonstrate cycle of approach, landing, perching, surveillance, take off, return in light to moderate winds. Demonstrate robust failure recovery. Demonstrate ability to do slow crawling and reorientation on the surface for better view. Demonstrate energy savings with jump-assisted takeoff and faster achievement of airspeed.		

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A Control System for Hovering

The control system for hovering is based on three sensors: a 3-axis accelerometer (ADXL330 rated at $\pm$3g), a 3-axis rate gyroscope (two IDG300 rated at 500 deg/sec) and a ultrasonic range sensor (SRF02). Both accelerometer and gyroscope are acquisitionned at 60Hz while the SRF02 is updated at 10Hz. The weight of all these sensors is less than 10 grams.

The idea of the control scheme is to combine the gravity vector measurement from the accelerometer at low frequency with the angular rate of the gyroscope at high frequency to get accurate attitude estimation for control. This filter eliminates the drift that we would result from the gyroscope integration, and provides accurate measurement at higher frequency than if the accelerometer alone was used. We are using a second-order complementary filter to combine the measurement in a simple and efficient way.

$$\theta(s)\left(\frac{\tau s+1}{\tau s+1}\right)^2 = \frac{\tau^2 s}{(\tau s+1)^2}\dot{\theta}_g(s) + \frac{2\tau s+1}{(\tau s+1)^2}\theta_a(s) \tag{1}$$

where $\dot{\theta}_g$ and θ_a are respectively the gyroscope and accelerometer measurements. A value of $\tau = 1$ rad/sec was found to provide an good balance between the gyroscope and accelerometer measurements.

Pitch and Yaw

The controller, for pitch and yaw, was first designed using the Ziegler-Nichols method, then transformed in a lead filter:

$$H_{yaw} = 2000\frac{s+5.3}{s+26.5} \tag{2}$$

Before being used by this controller, the pitch and yaw measurement are low pass filtered at about 15 Hz. The controller uses the input from the RC controller for trimming.

Roll

The roll controller consists of a proportional controller around the gyro measurement. It damps the roll motion enough so that the desired position is maintained through the hovering or perching maneuver. The signal from the gyro is also low-pass filtered at 2Hz.

Altitude

The SRF02 currently used for the altitude control has a fairly low update rate and a much shorter range than called for in the specifications. We are currently looking for a replacement. If the SRF02 is used alone, the combined sensor and motor delays produces large oscillations.

Stable hovering has been achieved using successive loop closure. An inner loop, based on the accelerometer measurement, eliminates the slow dynamics of the motor and sensor while the outer loop uses the SRF02 measurement to control the altitude. This result in stable altitude control.

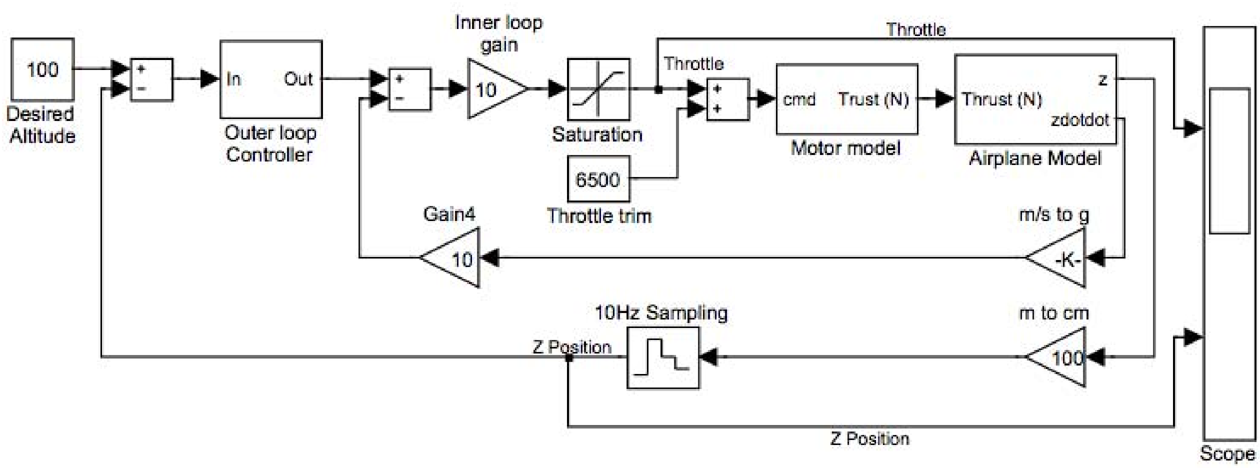

Figure 9: Diagram showing inner and outer loop for altitude control.