p.11 simulation coefficients
p.27 experimental coefficients

University of the
West of England

BRISTOL

Fold here

Surname ....

Forenames ....

....

Put label on dotted triangle

Assignment Cover Sheet

Instructions

- Put your name ONLY in the top right hand corner of this sheet. Fold the corner over and seal it so that your name cannot be seen.
- Do NOT put your name on the assignment
- Complete both parts of this form
- Attach this Cover Sheet securely to the assignment
- Submit the assignment to the **Education Student Reception**
- Ensure that the Receipt (below) is signed by a member of the Faculty's staff
- For postal submission: As above. The envelope must have a postmark date BEFORE the Due Date. Your receipt will be returned via the pigeon holes in **Education Student Reception**

By completing this page and in submitting this assignment you are declaring that it is your own work

Student Number	
Module Name	
Module Code	- -
Seminar Group (for Level 1 modules only)	
Due Date	Date Submitted

	You are strongly advised to keep a second copy of your work in case of any query about the assignment
Student Number	
Module Name	
Module Code	- -
Date submitted	

For Faculty Office use

Received by

Signed .... Date ....

Monopod Perching Quadrotor
Dissertation Report

Hao Wang

Supervisor: Dr Arthur Richards

Department of Engineering Mathematics

University of Bristol & University of the West of England

Content

Abstract 1
Introduction 1
Mathematical Modelling 3
1. Dynamic Equation of Monopod Perching Quadrotor 3
2. Actuator Modelling 4
3. Parameters Discussion and Table 5
1) Decide the Length of the Monopod 5
2) Parameters Table 6
System Analysis 7
1. Transfer Function of Plant & Motor 7
2. Pole Zero Map of Uncompensated Open Loop System 8
3. Impulse Response of Uncompensated Open Loop System 8
4. Step Response of Uncompensated Open Loop System 9
PID Controller 10
Simulation 11
1. Simulation Result without Outer Loop Controller 11
2. Simulation Result with Outer Loop Controller 13
Experiment 17
1. Build Monopod Perching Quadrotor 17
2. Landing 18
3. Performance 20
1) Experiment Results without Outer Loop Controller 23
2) Experiment Results without Limited Sensing (Apply Control Structure in Fig. 21) 24
3) Experiment Results with Limited Sensing (Apply Control Structure in Fig. 22) 25
Conclusion 29
Acknowledgements 29
Reference 29

Abstract

The research and development of the Unmanned Aerial Vehicles (UAV) has intensified considerably due to the interest of its wide application in military and commercial fields. This paper introduces a new type of quadrotor, called monopod perching quadrotor. This kind of quadrotor is built by giving quadrotor a leg, on which it can rest on an uneven site at reduced power. The advantage of the monopod over just landing is that the MAV is less dependent on finding even landing sites and can still yaw to survey an area. This report introduces a dynamic model of this quadrotor, as well as an entire landing and perching automatic control scheme. Classical PID controllers are employed into the control system. The report includes a simulation model for robust perching, with the control parameters used in this simulation successfully referenced by a one axis of experimental monopod perching quadrotor. The one axis of experimental monopod perching quadrotor is designed and fabricated basing on Quanser 3-DOF helicopter. The last part of this report shows the experimental results that illustrate the robustness of the control scheme and the performance for landing and perching.

Key word: monopod perching quadrotor, dynamics, landing, perching

Introduction

Recently, quadrotor flying robots have successfully attracted the attention of many researchers in the field of automation, robotics and aviation due to their tremendous advantages [1]. As a helicopter, quadrotors have evident strengths over other aircraft since it is a kind of vertical take-off and landing UAV with a really simple structure. Also, quadrotors are ideal platforms in unknown and complex environments. Their small size and manoeuvrability are conducive to operating in confined spaces and avoid obstacles. Furthermore, if equipped with appropriate sensors and algorithms, quadrotors can serve several tough tasks which currently are infeasible for ground robots. For example, a swarm of quadrotor vehicles can be deployed to search for survivors after an earthquake.

However, some difficulties have to be faced when designing and controlling a quadrotor. For example, since a quadrotor is an under-actuated system with nonlinear and coupling characteristics, it becomes a challenging task to control a quadrotor in a real and complex environment. Also, its fast dynamics that support its manoeuvrability require accurate and frequently updated position, orientation and velocity information, but the payload available on a quadrotor may limit the available sensors and processing capability. Moreover, the cruising distance may have to be considered in a bespoke design.

Although they have a lot of difficulties, quadrotors have always exerted a great fascination encouraging all kinds of research and development. The interest comes not only from its dynamics, which represent an attractive control problem, but also from the design issue. Integrating the sensors, actuators and intelligence into a lightweight vertically flying system with a decent operation time is not trivial.

In the past few years, different control methods have been explored for the attitude and position control of quadrotors. The thesis [2] lists some of the most important quadrotor projects in recent years. Some most used control methods include PID, LQR, Sliding Mode, and Backstepping. For example, in [3] and [4], A PD controller was introduced and its performance was discussed to control the quadrotor. In [5], there are two non-linear control techniques applied to a quadrotor. They are Backstepping and Sliding Mode techniques. Also, [6] suggests the results that the discrete LQR controller combining with the EKF are a good strategy for estimating and controlling the attitude of a quadrotor. Some of the most used sensors include gyroscopes, manometers, compass and accelerometers. Since most sensors cannot be one hundred percent trusted by researchers, a quadrotor may use one or more sensors to acquire information, and then analysis these data to find an accurate value. As a result, some filter algorithm have been adopted and applied, such as complementary filter and Kalman filter. For example, in [7], 3-axes MEMS accelerometers, a 3-axes MEMS rate-gyros, and an electronic compass were used to form an Attitude and Heading Reference System (AHRS). Kalman filter was employed as an option of multi-sensor data fusion. Also, in [8], two sensors (3-axis gyroscope and 3-axis accelerometer) are employed. With the aim of improving the quality of the aerial vehicle control, then [8] presents the experimental comparison between two sensor data filtering algorithms: complementary filtering and Kalman filter.

In this essay, our interest is in the design of control schemes to support autonomous landing and perching. A new type of UAV called monopod perching quadrotor is introduced and discussed. This concept is to extend the endurance of a quadrotor micro air vehicle by giving it a leg, on which it can rest at reduced power. This kind of quadrotor has several advantages when applied into real use. An example is that when implementing tasks in some extreme or special places, the quadrotor’s endurance are probably required. On one hand, a quadrotor with a leg could enable the applications since it is less dependent on finding even landing sites and can still yaw to survey an area. On the other hand, the leg is able to help quadrotor to reduce power, since the rotors will run slowly after successfully perching.

In this report, our focus of research using this quadrotor include building a dynamic model and designing and implementing feasible control schemes to support its automatic landing and perching. The controllers are able to stabilize the monopod perching quadrotor. The control systems are standalone and easy to use such that other controllers can be implemented as desired.

Mathematical Modelling

1. Dynamic Equation of Monopod Perching Quadrotor

A quadrotor is an under actuated systems with four rotors as is shown in Fig. 1. Modelling such UAV is not an easy task due to its complex structure. In the quadrotor, each rotor has a fixed angle that can represent an input force, and all together produce 4 input forces which are basically the thrust provided by propellers.

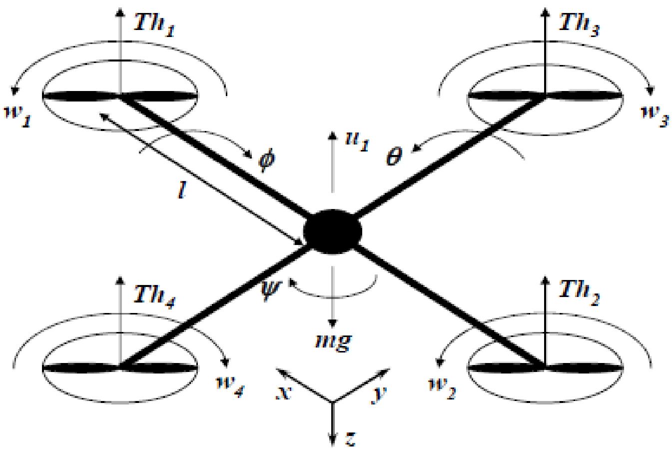

Figure 1 The quadrotor schematic [9]

Motion can be realized through changing the speed of 4 rotors. For example, forward motion can be achieved by increasing speed of the front motor while decreasing rear rotor speed simultaneously, which means that the pitch angle will be changed. Left and right motion is achieved by changing roll angle with the same method. By increasing (reducing) the speed of the right rotor while reducing (increasing) the speed of the left rotor, the roll movement is obtained. When the front and rear motors rotate counter-clockwise while other motors rotate clockwise, then yaw command can be derived simply by increasing counter-clockwise motors speed while decreasing others. In this way, this symmetry of the quadrotor body gives simplicity to the analysis and design since the influence on pitch does not affect the performance on roll. Although the yaw command is derived by changing 4 rotors, temporarily its performance will not be discussed. For the purpose of simplicity and clarity, only half body structure will be considered to discuss the monopod perching quadrotor according to its symmetric characteristics.

A basic schematic of one axis of monopod perching quadrotor is shown as Fig. 2.

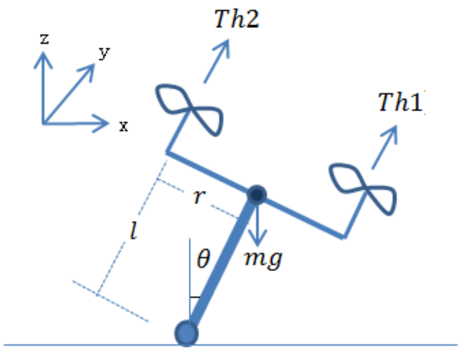

Figure 2 Schematic of one axis of monopod perching quadrotor

Each rotor produces vertical forces as well as moments. These moments have been experimentally observed to be linearly dependent on the forces for low speeds [9]. The center of gravity is assumed to be in the middle of the connecting link. The dynamic model of the monopod perching quadrotor can be obtained via the Newton Second Law for Rotation approach and its dynamic equation is given as follow.

$$(Th2 - Th1) * r + mg * l * sin(\theta) = m * l^2 * \theta'' \quad (1)$$

Where

Th1, *Th2* are the thrust force produced by the propellers.

r is the radius(from centre of propeller to centre of gravity)

m is mass, *g* is acceleration of gravity.

l is the length of leg, and θ is the tilt angle (also pitch angle) from upright vertical.

$m * l^2$ is the mass moment of inertia.

Some assumptions and cancellations were considered before building this model, as follows:

1) The whole structure of quadrotor is assumed as symmetrical and rigid.

2) The totally mass is assumed in the centre (link connection point) of the structure.

3) Only thrust levels involved will be discussed. Propeller behaviours were unnecessary to be considered.

This quadrotor model has 2 independent inputs (*Th1*, *Th2*) while 1 output (θ), and there is one degree of freedom (1 DOF). This makes it easy that controlling the state as it’s no longer an under-actuated system. A good controller is able to keep this system stable with consuming less power.

2. Actuator Modelling

The actuation mechanism consists of four DC motors. The response of a brush DC motor with the voltage e_i (in V or volts) considered as an input and the angular velocity ω (in rad/s) as an output, can be approximately described by a first-order differential equation[10]:

$$\tau \frac{d\omega}{dt} + \omega = ke_i \quad (2)$$

Where
e_i is voltage, and ω is the angular velocity of the motor shafts.
τ is time constant, which relies on load drive, and k is steady state gain.

The motor will be run if supplied with the required voltage, and the thrust is proportional to angular velocity directly. That is, whenever increasing the angular velocity, the thrust for the motor will increase and vice versa.

3. Parameters Discussion and Table

1) Decide the Length of the Monopod

Among those variables that will have an effect on the stabilization of the quadrotor system, the length of the monopod greatly determines a major part of its motion. Since the length of monopod will influence the torque and mass moment of inertia, from dynamic equation we know that it will influence the stability of our overall system.

Before discussion of the length of leg, we need to decide the saturation of thrust which is decided by motors. To choose a motor we first need to know how much weight to take, and then to work out the thrust required to lift the quadrotor. A general rule is that we should be able to provide twice as much thrust than the weight of the quadrotor [11]. If the thrust provided by the motors are too little, the quadrotor will not respond well to the control, and even has difficulties to take off. But if the thrust is too much, the quadrotor might become too agile and hard to control.

A rule of thumb is

$$Thrust_{required} = \frac{2 * mg}{4} \ OR \ 50\% * Thrust_{required} = \frac{mg}{4} \quad (3)$$

That means 50% of the required thrust from one motor is equal to 1/4 of the weight of the quadrotor. The thrust produced by each motor make quarter contribution to overcome the gravity, and each rotor goes 50% of its maximum value.

The max thrust, as a result, is assumed to be produced when the rotor on one side goes to 100% of the maximum and the other side goes to 0%. The equation of the max thrust and torque for the system is

$$Th2 - Th1 = (100\% - 0\%) * Thrust_{rated} = 100\% * \frac{2 * mg}{4} \quad (4)$$

$$M = (Th2 - Th1) * r = \left(100\% * \frac{2 * mg}{4}\right) * r = \frac{1}{2} * mg * r \quad (5)$$

Recall our dynamic equation for monopod perching quadrotor then can be looked as:

$$M + mg * l * sin(\theta) = m * l^2 * \theta'' \quad (6)$$

One can derive that

$$\theta'' = \frac{\frac{1}{2} * mg * r + mg * l * \sin(\theta)}{m * l^2} \quad (7)$$

After simplification,

$$\theta'' = \frac{\frac{1}{2} * g * r + g * l * \sin(\theta)}{l * l} \quad (8)$$

From equation (8), one can find that the relationship between angular acceleration θ'' and length of leg l if setting θ, g, r as constant values. The acceleration of the quadrotor will depend inversely on the length of the leg. So a longer monopod within limiting range will mean that it will fall slower and so be easier to balance but also be more massive and harder to accelerate at a given rate.

The critical value of angular acceleration required to keep the monopod from failing is found by setting $\theta'' = 0$ and θ = *Maximum tilt angle*. Then one can have following equation to find the maximum length of leg.

$$\frac{1}{2} * r + l * \sin(\theta_{max}) = 0 \quad (9)$$

$$l_{max} = \left| \frac{\frac{1}{2} * r}{\sin(\theta_{\max})} \right| \quad (10)$$

For example, when r is 0.18 meters and θ_{max} is $5 * \frac{pi}{180}$ radians, $l_{max}$is around 1.03 meters.

2) Parameters Table

The physical parameters of the system prototype are tabulated as follows:

variables	Physics	quantity
$\boldsymbol{m}$	Mass of Quadrotor	1.15 kg
$\boldsymbol{l}$	Length of Leg	0.3 m
$\boldsymbol{r}$	Radius	0.18 m
$\boldsymbol{g}$	Gravity	10 m/s^2
$\boldsymbol{k}$	Steady State Gain	1
$\boldsymbol{\tau}$	Time Constant	1

Table 1

N.B.

1. k and τ are only applied for simulation.

2. Quanser Parameters can be obtained from Quanser Official Website.

(Website Link: http://www.quanser.com/products/3dof_helicopter)

System Analysis

1. Transfer Function of Plant & Motor

The plant dynamic equation contains non-linear component $sin(\theta)$. Since the analysis and design techniques that will be used in this paper only apply to linear systems, this equation is required to be linearized. Many systems in real world are non-linear but can be linearized for easier analysis purpose, and this system is no different. Specifically, we will linearize the equation about the vertically upward equilibrium position, that is, $\theta = 0$, assuming that the system will stay in a very small neighbourhood of this position.

This assumption should be reasonably valid because under landing control we desire that the quadrotor not deviate more than 5 degrees from the vertically upward position. And by applying small angle approximations of nonlinear functions in our system equation:

$$sin(\theta) = \theta \quad (11)$$

After substituting the above approximation into our dynamic equations, we arrive at the following equation:

$$M + mg * l * \theta = m * l^2 * \theta'' \quad (12)$$

The transfer function of the linearized system equation is:

$$\frac{\theta(s)}{M(s)} = \frac{1}{m * l^2 * s^2 - m * g * l} \quad (13)$$

Where the angle $\theta(s)$ is considered the output and the moment $M(s)$is considered the input.

We will also have a look at the angular velocity as the output. We can obtain the angular velocity by differentiating the angle. Therefore, we need to multiply the above transfer function by s. The equation is

$$\frac{\dot{\theta}(s)}{M(s)} = \frac{s}{m * l^2 * s^2 - m * g * l} \quad (14)$$

The dynamics of motor is described by a first order equation. The transfer function representation of the motor model is

$$\frac{\dot{\varphi}(s)}{E_i(s)} = \frac{k}{\tau s + 1} \quad (15)$$

In this paper, the thrust and its moment is regarded as directly proportional to rotor angular velocities, that is,

$$M(s) = k' * \dot{\varphi}(s) \quad (16)$$

where k' is constant.

(*N.B.* $k' = 1$ in following discussions.) Why?

Then the open loop and linearized transfer function for the whole uncontrolled system can be given as:

$$\frac{\theta(s)}{M(s)} = \frac{kk'}{(m * l^2 * s^2 - m * g * l)(\tau s + 1)} \quad (17)$$

2. Pole Zero Map of Uncompensated Open Loop System

The poles position of the linearized model of whole quadrotor system shows that system is not stable, since one of three poles of the transfer function lies on the right half side of the s-plane. Thus the system is unstable. The pole zero map is in Fig. 3.

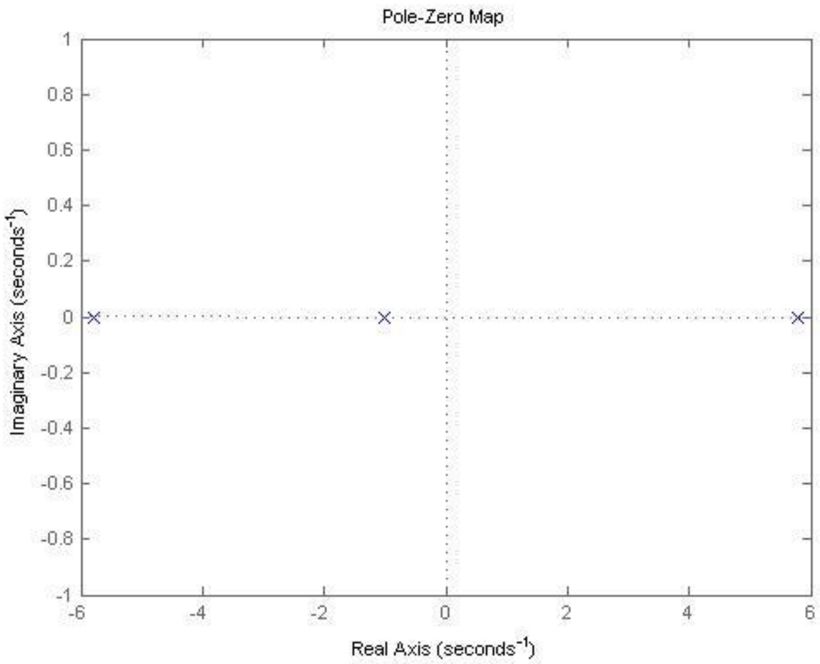

Figure 3 Pole Zero Map

3. Impulse Response of Uncompensated Open Loop System

An impulse response of the system is shown in Fig. 4. The plot shows that the system is highly unstable as θ changes very rapidly. The runaway nature of the response indicates instability.

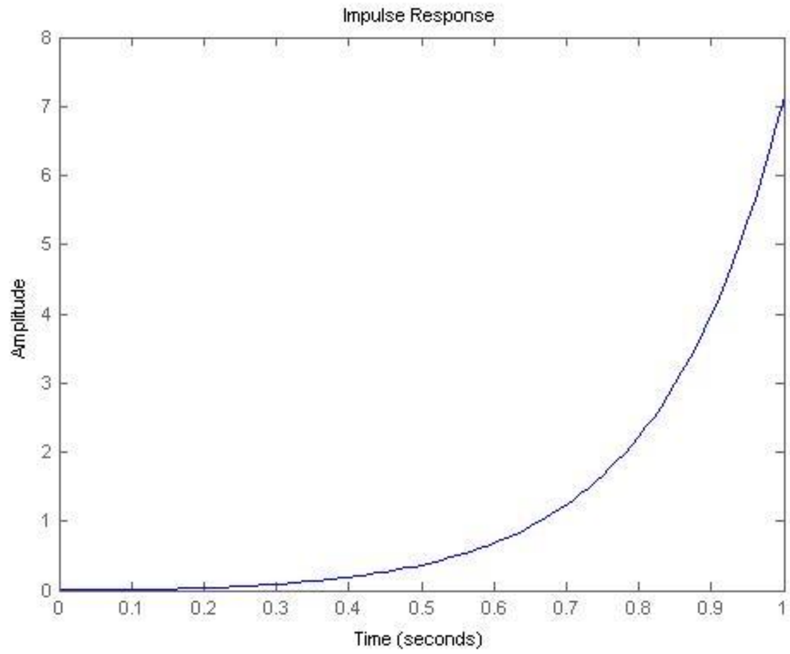

Figure 4 Impulse Response

4. Step Response of Uncompensated Open Loop System

A step response of the system is shown in Fig. 5. The plot shows that the system is highly unstable as θ diverges very rapidly and grows unbounded. The runaway nature of the response indicates instability.

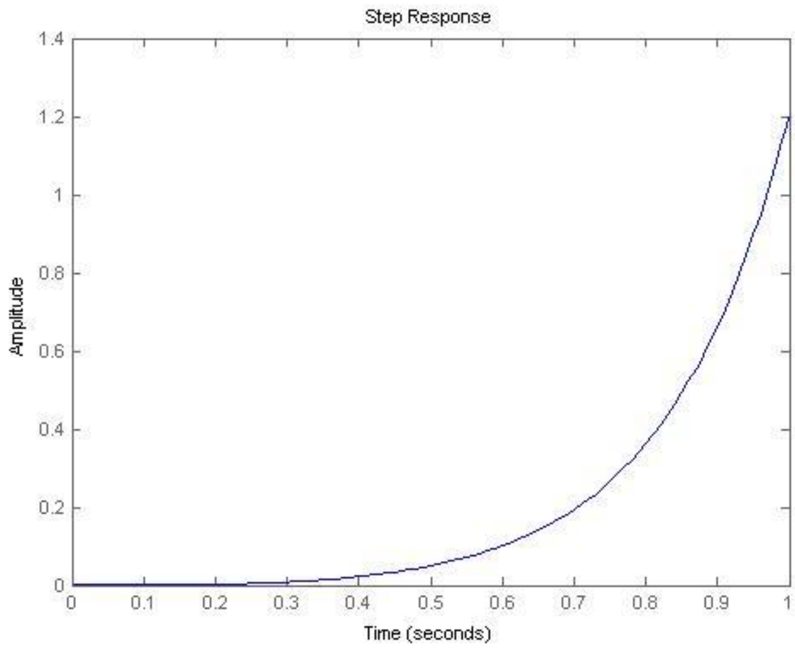

Figure 5 Step Response

It is apparent from the analysis above that some sort of control will need to be designed to improve the response of the system. The control scheme should enable the system that has all its roots in the left half plane (stable region) of the s-plane.

PID Controller

The proportional Integral derivative (PID) design is discussed in many references, such as [9] and [12]. PID controllers can be used only for plants with relatively small time delay for high performance devices like the quadrotor. A PID controller takes many forms but the general one has the following structure:

$$u(t) = K_p e(t) + K_i \int_o^t e(\tau)d\tau + K_d \frac{d}{dt} e(t) \quad (18)$$

Where u(t) is the output of the controller as well as input of the plant, *e(t) = SP – PV*. *PV* is the measureable output value while *SP* is its desired value. $K_p, K_i,$ and K_d are gains.

The main aspect of the controller selection depends on the purpose of controlling the UAV. A desired control scheme here is able to stabilize the quadrotor and is capable of the steadily perching of the vehicle. In this paper, a cascade control strategy involving two control loops (inner and outer) is adopted. The inner controller controls the output of angular (pitch) rate while the outer one controls the pitch angle.

There is one thing we need to notice. In real world, there are gyros that are capable of directly measuring angular rate. Accelerometer and gyroscope are hard to use separately to measure the Euler angle [13]. The Euler angles are three angles introduced by Leonhard Euler to describe the orientation of a rigid body, including roll, pitch and yaw. In order to measure accurate Euler angles, some researchers combine different sensors as well as introduce appropriate filters. For example, [13] introduces detailed procedures of getting the accurate and reliable Euler angles with accelerometer, gyroscope and Kalman fusion.

In this report, we assume that we can measure both pitch rate and angle in simulation. The one axis of experimental monopod perching quadrotor in the lab are able to measure these values. One need to pay attention that the accurate angle measurement may not available for a real quadrotor with limited sensing. So this report in experiment part introduces a method that is able to rotate the quadrotor to roughly upright when the real quadrotor has limited sensing.

In the simulation, the control strategy will work in this way. The inner controller will quickly control the angular rate to zero. In this stage, the quadrotor is able to stand still but might not be vertically upward. The next stage is that the outer controller will work gently and slowly rotating the quadrotor to upright.

The inner loop plant P1(s) is

$$\frac{\dot{\theta}(s)}{E_i(s)} = P1(s) = \frac{kk's}{(I*s^2 - m*g*l)(\tau s+1)} \quad (19)$$

The outer loop plant P2(s) is

$$P2(s) = \frac{C1(s)P1(s)}{1+C1(s)P1(s)} * \frac{1}{s} \quad (20)$$

Where

C1(s) is the transfer function of inner loop controller.

The simple schematic of control structure is shown as Fig. 6.

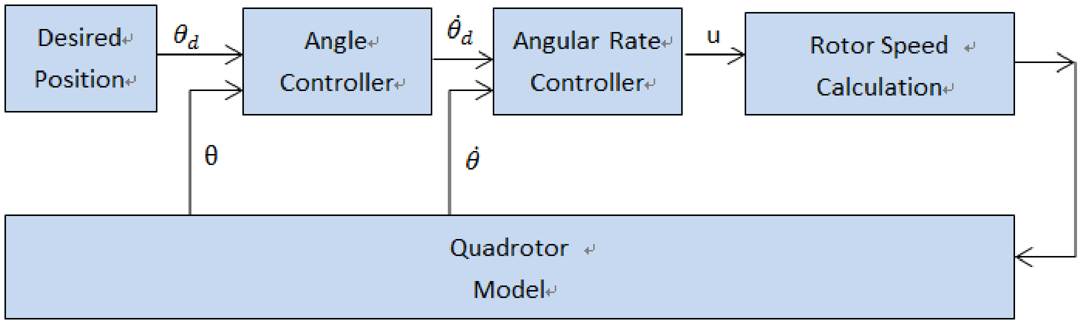

Figure 6 Schematic of perching control structure

The best way to design a cascade control scheme is to design the inner loop controller first and then design the outer loop controller with the inner loop closed [14].

The angular rate controller is designed first. K coefficients which are used for the angular rate controller are derived by substituting equations (19) & (20) and using automatic tool 'pidtool' within Matlab for best performance. K coefficients that are used for the angle controller are derived by trial and error for best performance. A P controller for the outer loop is performed very well in maintaining stability and the response of control.

Simulation

The controller parameters and initial conditions of the quadrotor for simulation are:

Rate Controller (inner loop): $\mathrm{K_p} = 130, \mathrm{K_i} = 115, \mathrm{K_d} = 12, \mathrm{N(FiterCoefficient)} = 236$

Angle Controller (outer loop): $\mathrm{K_p} = 1$

$\theta(0)$ = 5 degrees

Impulse Disturbance: Moment = 0.2 Nm

1. Simulation Result without Outer Loop Controller

The inner loop control system can be shown in Fig. 7, which is composed of reference signals, an angular rate controller, saturation function (limits maximum/minimum moment), actuator and plant. The quadrotor is initially started with a 5 degree tilt angle and its response of angular rate and angle can be seen in Fig. 8 and Fig. 9. A nonlinear plant model was used in the simulation.

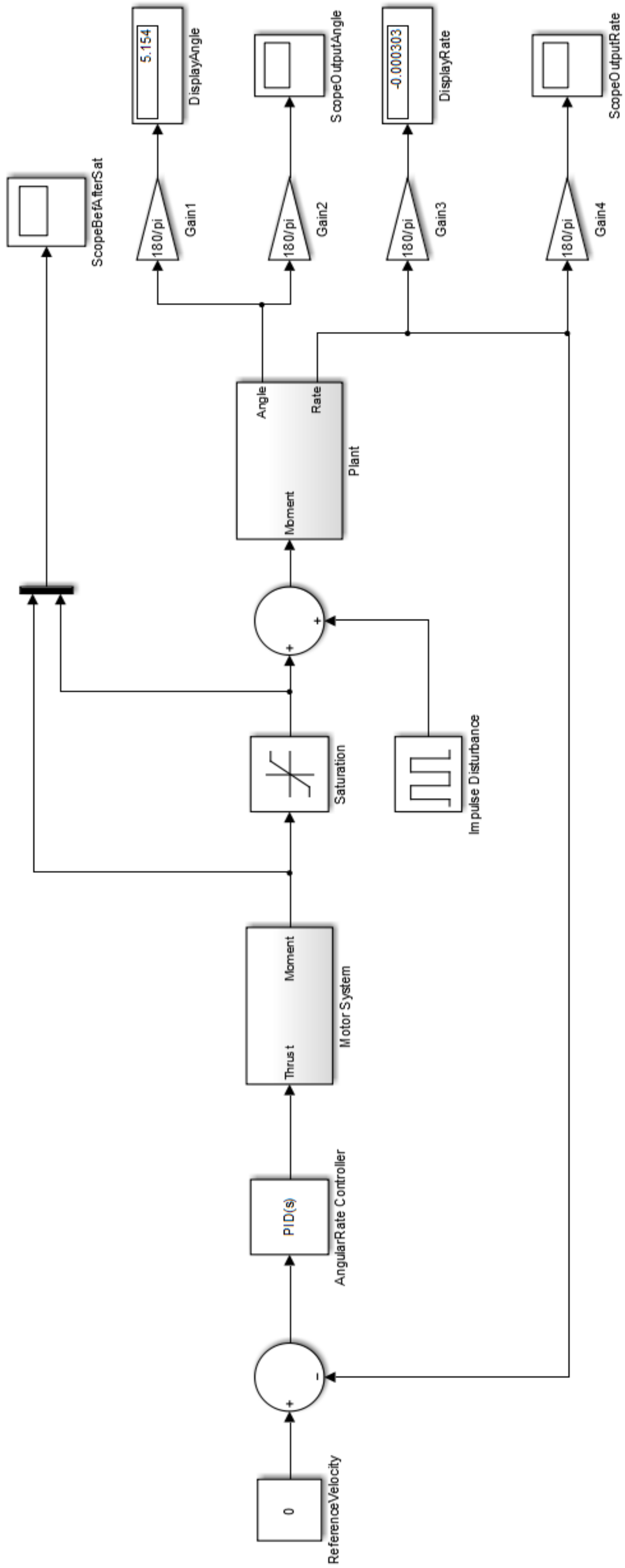

Figure 7 Simulation Model without Outer Loop Controller

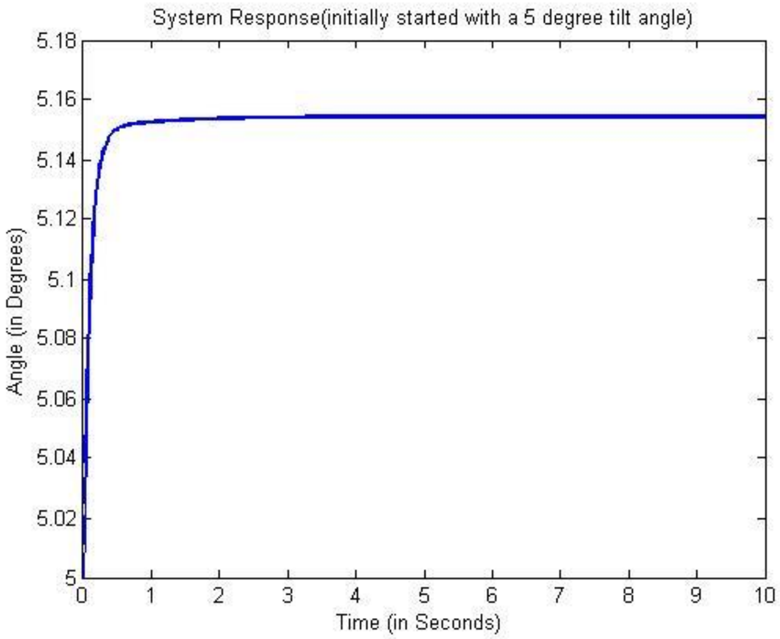

Figure 8 Response of Angle

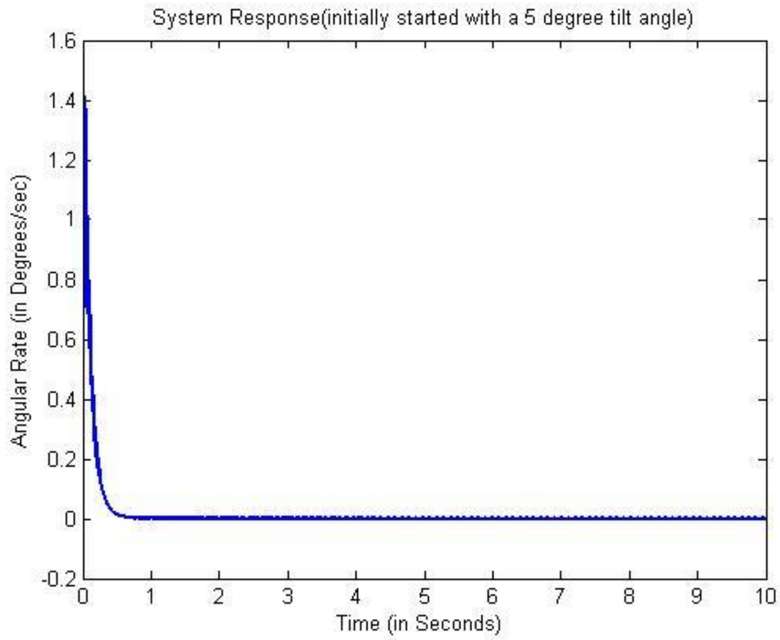

Figure 9 Response of Angular Rate

The simulation results show that the angular rate controller works well. The control system is stable within 4 seconds. The steady state error of angular rate goes to zero after 1 second, and the quadrotor moves less than 0.2 degrees away from its initial position.

2. Simulation Result with Outer Loop Controller

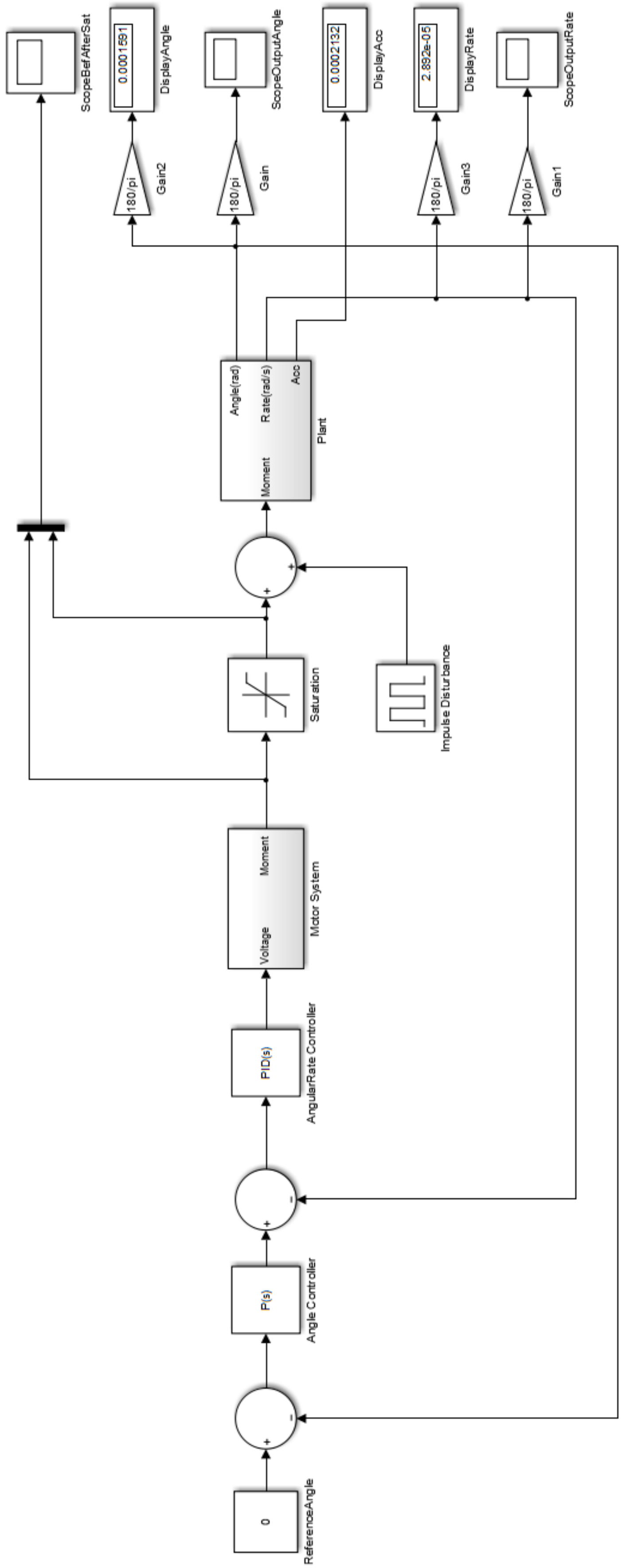

Figure 10 Simulation Model with Outer Loop Controller

The proposed simulation control model is shown in Fig. 10, which is composed of reference signals, all controllers, saturation function, actuator and plant. The quadrotor is initially started with a 5 degree tilt angle and its response of angle and angular rate can be seen in Fig. 11 & Fig. 12. The system is stable within 7 seconds.

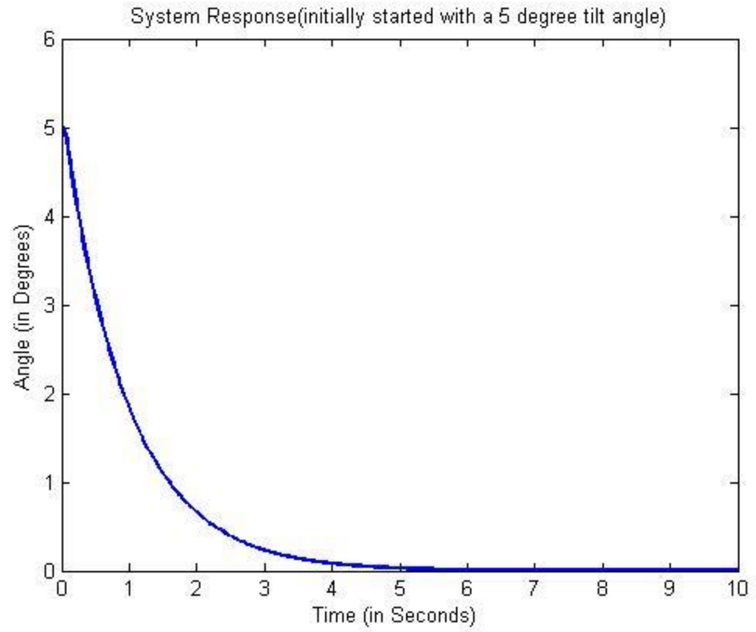

Figure 11 Response of Angle (initial tilt angle equal 5 degrees)

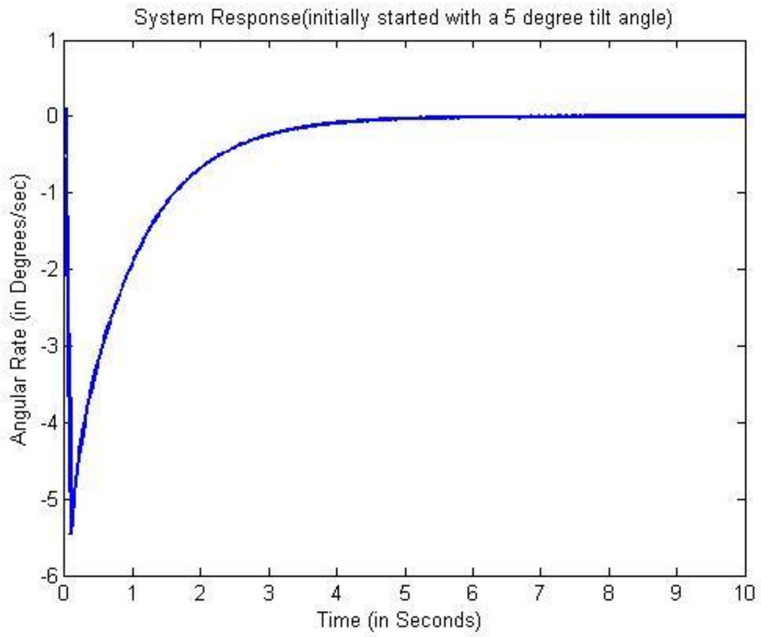

Figure 12 Response of Angular Rate (initial tilt angle equal 5 degrees)

If given a 5 degree tilt angle at start with an impulse disturbance (For example, the disturbance may come from a gust of wind), then the response of system can be seen in Fig. 13 & Fig. 14. The system becomes stable in 7 seconds.

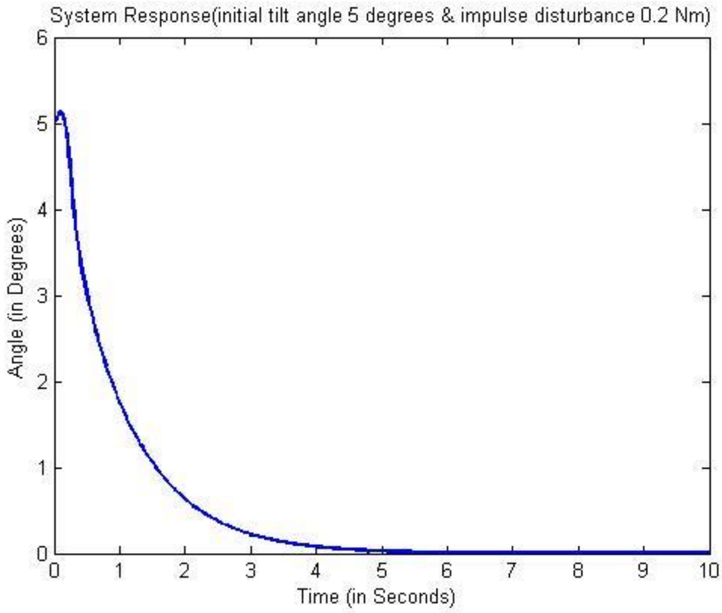

Figure 13 Response of Angle (initial tilt angle equals 5 degrees & initial impulse disturbance equals 0.2 Nm)

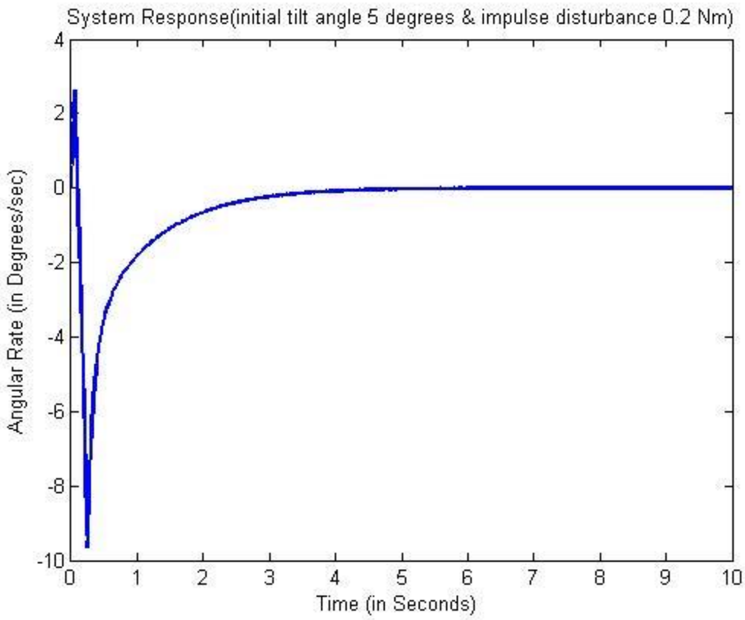

Figure 14 Response of Angular Rate (initial tilt angle equals 5 degrees & initial impulse disturbance equals 0.2 Nm)

The simulation results show that the Cascade Control System is able to robustly stabilize the quadrotor helicopter and move it to a vertically upright position very smoothly within seconds. The quadrotor does not tilt severely at settling time, and the angular rate value never goes beyond control. The rate controller quickly settles the angular rate to the neighbour of desired value and the angle controller steadily and slowly rotates the quadrotor to upright. The angle controller performs slowly compared to the rate controller. The good performance of controller can be shown from its quite fast response, and simulation verifies the effectiveness of the design of the control method.

But the simulation results can only be used as a reference, which means the parameters cannot be directly used for the actual landing or that the real performance will be same. Therefore, a real test was designed at University of Bristol Dynamics Laboratory, through which the parameters and performance can be finally obtained.

Experiment

1. Build Monopod Perching Quadrotor

In order to do the test, a one axis of experimental monopod perching quadrotor was designed by employing and re-assembling the Quanser 3-DOF helicopter. The original Quanser 3-DOF helicopter is composed of a model helicopter body, a metal base, and an aluminium frame. The helicopter has two propellers mounted in parallel, which used to control the movement of the helicopter. The two propellers actuated by two DC motors. Also, high-resolution encoders are available to get precise position feedback. The overall mechanical structure is very simple and practical, and meets the basic requirements of the design of adding a leg to the body structure.

A leg is designed and built using a thin wooden stick. It was fixed to the body using a piece of cardboard and several binder clips. A tiny rubber is added to the bottom of the leg. The total weight of leg is very small compared to the helicopter and thus can be omitted. The actual length of leg is 0.25 meter (the length from foot to mass point is 0.3m, in coincidence with previous analysis). The leg can be reliably fixed to the helicopter body as well as easily removed. The whole structure of one axis of monopod perching quadrotor is presented in Fig. 15.

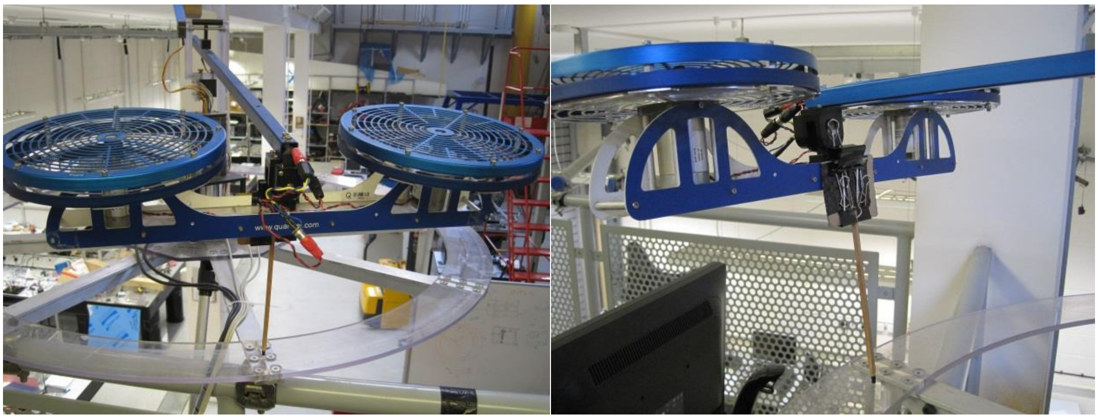

Figure 15 The structure of one axis of monopod perching quadrotor front view (left) & rear view (right)

The helicopter is free to pitch about its centre. Also, the helicopter is able to rotate about the vertical axis - the travel axis - as well as up and down - the elevation axis. The precise position feedback can be obtained by employing high-resolution encoders.

2. Landing

The landing process is very important for the one axis of monopod perching quadrotor since we desire that the quadrotor can land reliably and the elevation and its rate will slowly turn to 0.

An existing PID controller is able to be directly employed for landing. However, its performance has not satisfied our requirement. Since the landing process is too fast and the quadrotor nearly free falls to 'hit' the ground, instead of 'reach' or 'touch'. This causes the problem that the quadrotor will 'jump' one or more times, and it is nearly impossible to land steadily on an uneven site, such as a slope.

When a one axis of monopod perching quadrotor stands vertically on the ground, we assume the elevation is 0. The previous existing PID controller set reference elevation signal to 0. When a 'landing' signal is sent, the vehicle falls rapidly and hit the ground. Then the vehicle body begins to tilt and the tilt angles may exceed more than 10 degrees. This is unacceptable, since we desire that such tile angles after landing are within 5 degrees. Therefore, a modified PID controller for landing is introduced. Instead of using a constant reference signal 0, a ramp signal is used. The initial output of ramp signal is the vehicle's elevation value, which can be measured by a sensor. The slope of ramp signal is set as -0.0001, which is derived by trial and error for best performance. The lower limitation of this signal can be set as 0. The gains of controller are $\mathrm{K_p} = 1, \mathrm{K_i} = 1, \mathrm{K_d} = 1$. The 'gentle landing' technique structure is shown as Fig. 16.

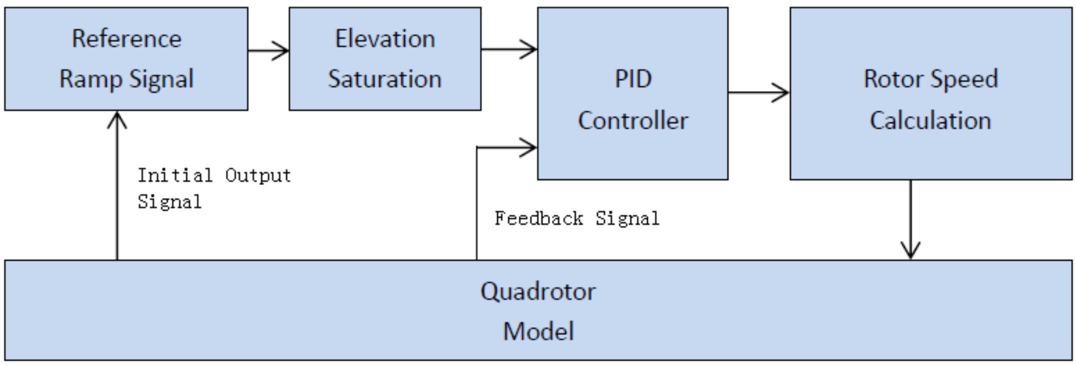

Figure 16 Schematic of landing control structure

The comparison results for landing with and without 'gentle landing' technique are shown as Fig. 17 & Fig. 18 & Fig. 19.

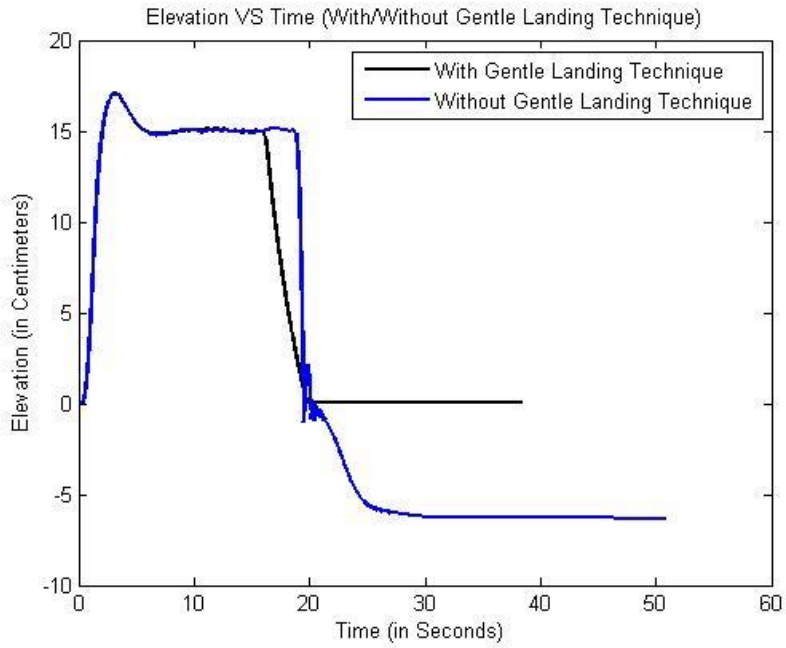

Figure 17 Elevation Results of the landing experiment

Fig. 17 shows elevation changes after a 'landing' signal is sent. The vehicle lands from 15 centimeters high. It takes about two seconds to land on the ground with the 'gentle landing' technique. The vehicle falls faster without the 'gently landing' technique. The vehicle without applying 'gentle landing' technique lands on the ground at 20 seconds, and then it starts to tilt (Fig. 18). Since the elevation is zero when the quadrotor is upright on the ground, the elevation (blue lines) decreases (centre of gravity descends) and becomes negative after 20 seconds.

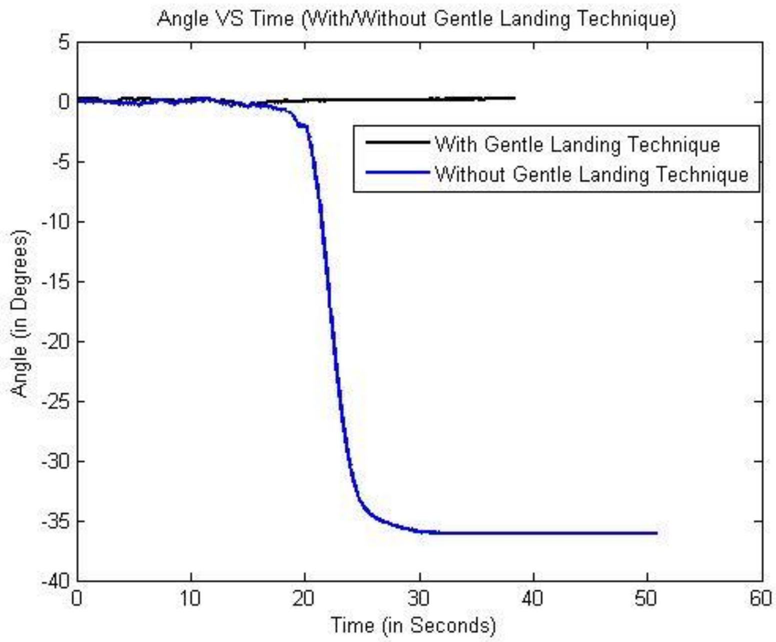

Figure 18 Angle Results of the landing experiment

Fig. 18 shows that the vehicle without ‘gentle landing’ technique tilts rapidly after landing and that the ‘gentle landing’ technique can limit the tilt angle changing.

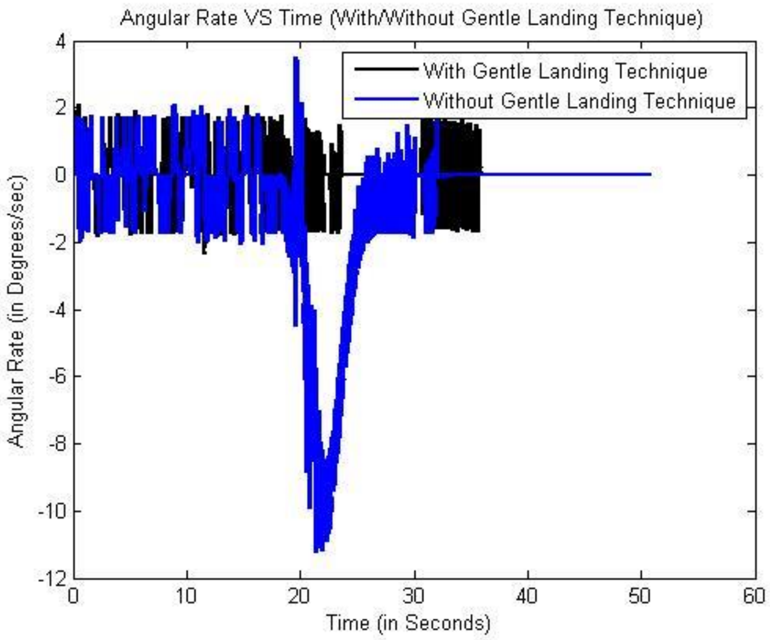

Figure 19 Angular Rate Results of the landing experiment

The ‘gentle landing’ technique works well and it allows the quadrotor slowly, gently and steadily landing to the site.

3. Performance

Previously we describe a series of PID controllers from former sections. Two controllers, a rate PID-controller and an angular P-controller constitute the Perching Subsystem. A Modified PID controller is the main component of Landing Subsystem. These two subsystems will start to work when a ‘land’ signal is sent. Then the whole process will be totally automatic. That is, as the Landing Subsystem settles its elevation, the Perching Subsystem settles its pitch rate and pitch angle. Finally the whole structure will be upright with slow rotor rotation. A diagram illustrating the process is shown as Fig. 20.

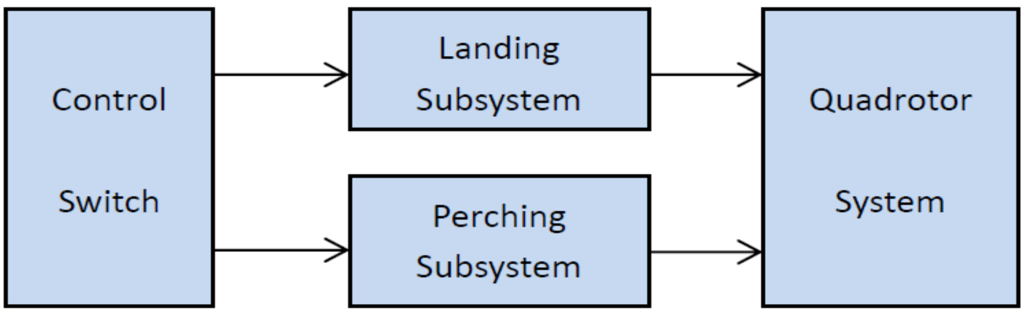

Figure 20 Automatic control strategies

In QUARC real-time control software for MATLAB®/Simulink®, the whole structure is shown as Fig. 21 and Fig. 22.

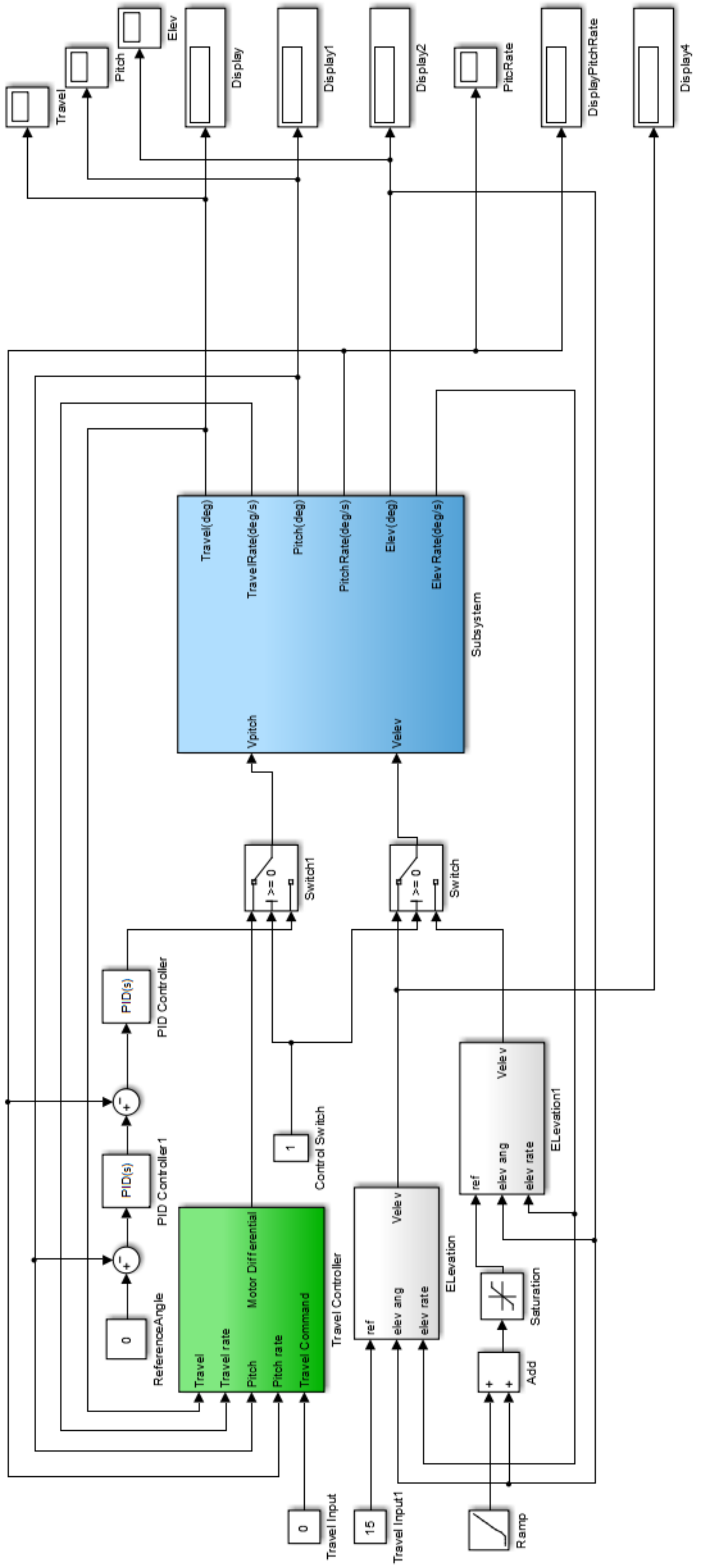

Figure 21 Control Structure in Software

In the one axis of experimental monopod perching quadrotor, the pitch angle can be measured by a sensor. Then the control structure can be presented as Fig. 21. The pitch angles are feedback signals for the outer loop controller. However, if we assume limited sensing, then the pitch angle may not be available. Instead, we will use the pitch control setting as the controlled variable for the outer loop. It means that we will slowly drive the two voltages to be the same. Then we can assume the vehicle can be roughly upright. This control structure is presented as Fig. 22.

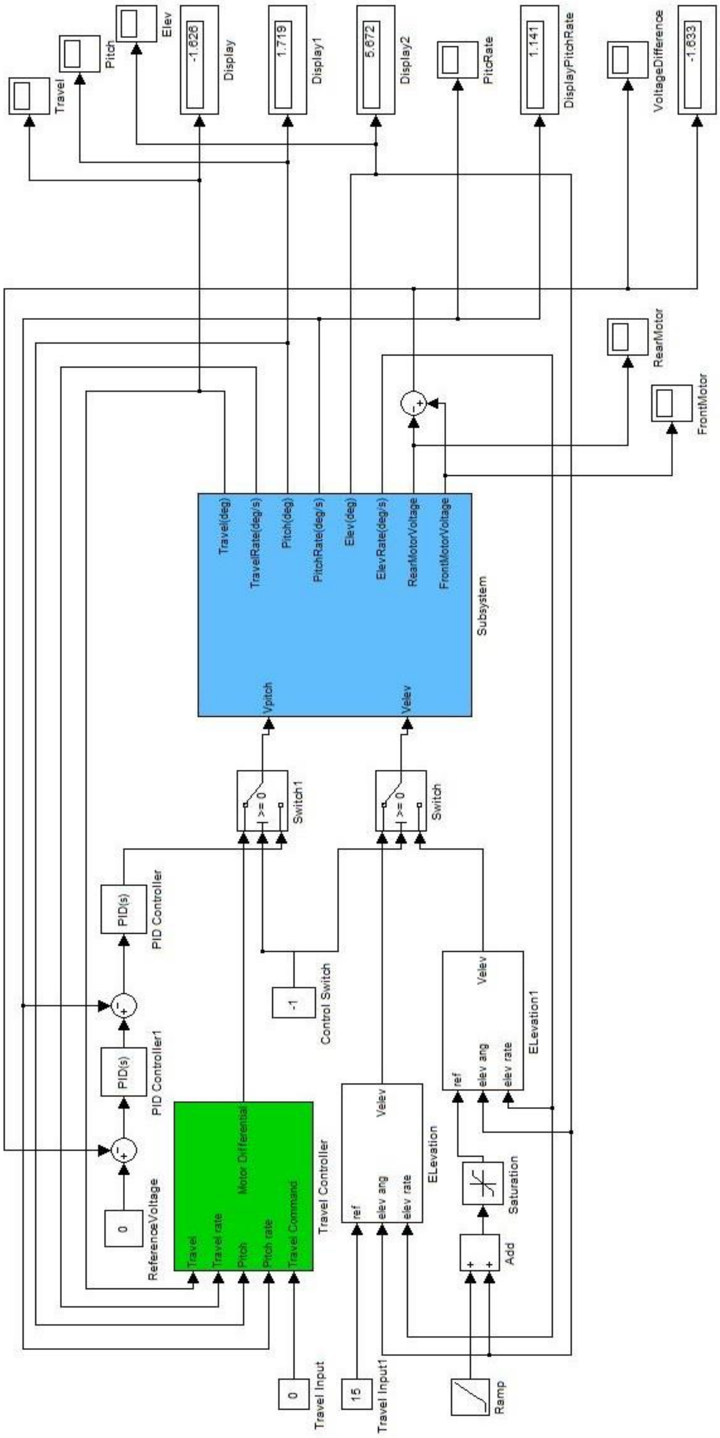

Figure 22 Control Structure in Software (Limited Sensing)

When doing the test, Firstly, we take off by setting the control switch parameter greater than 0, so that the quadrotor will be hovering. After a few seconds, the ‘land’ command is sent. This is done by setting the control switch parameter less than 0, and the quadrotor is required to land on an even or uneven sites. Such tests have shown that both Landing Subsystem and Perching Subsystem are robust in response of landing signals. The analysis data can be collected by high-resolution encoders carried by the vehicle, and transferred to the computer.

1) Experiment Results without Outer Loop Controller

The experiment results in Fig. 23 & Fig. 24 & Fig. 25 show the performance of inner loop angular rate controller.

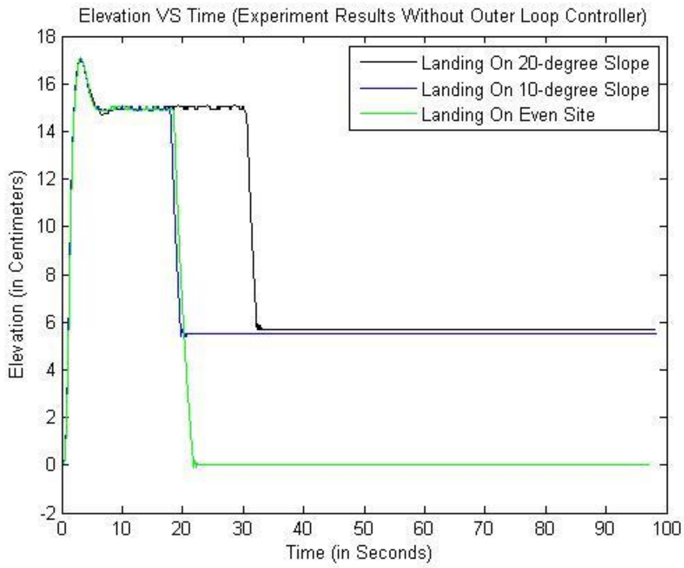

Figure 23 Elevation Results of Experiment

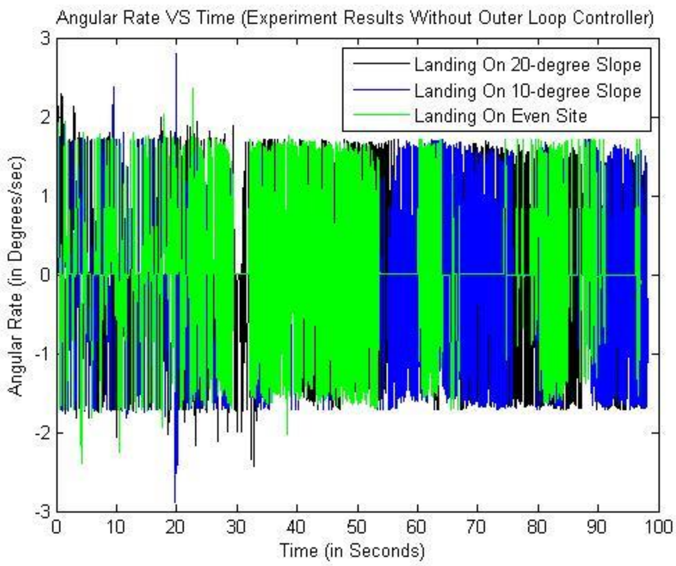

Figure 24 Angular Rate Results of Experiment

From Fig. 23, one can see that the angular rates show a bounded oscillation of 2 degrees/sec in amplitude. This is hardly captured by human eyes. The one axis of experimental monopod perching quadrotor is successfully stabilized although there are small fluctuations.

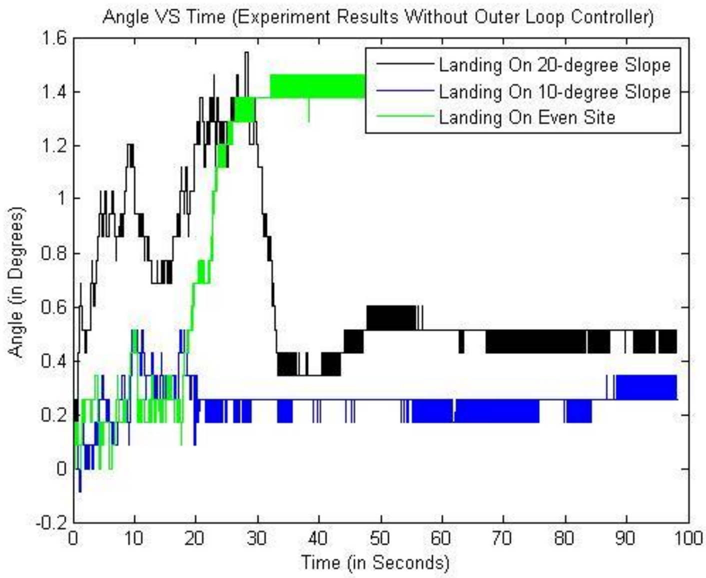

Figure 25 Angle Results of Experiment

2) Experiment Results without Limited Sensing (Apply Control Structure in Fig. 21)

The experiment results in Fig. 26 & Fig. 27 & Fig. 28 show the performance of the control system.

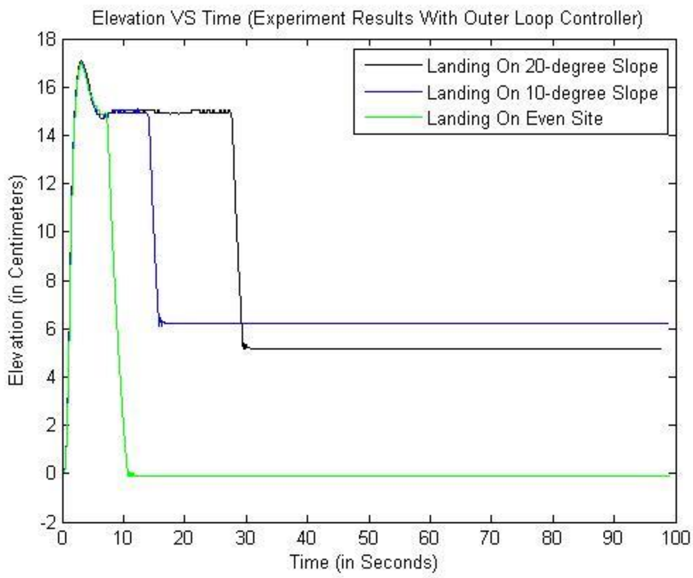

Figure 26 Elevation Results of Experiment

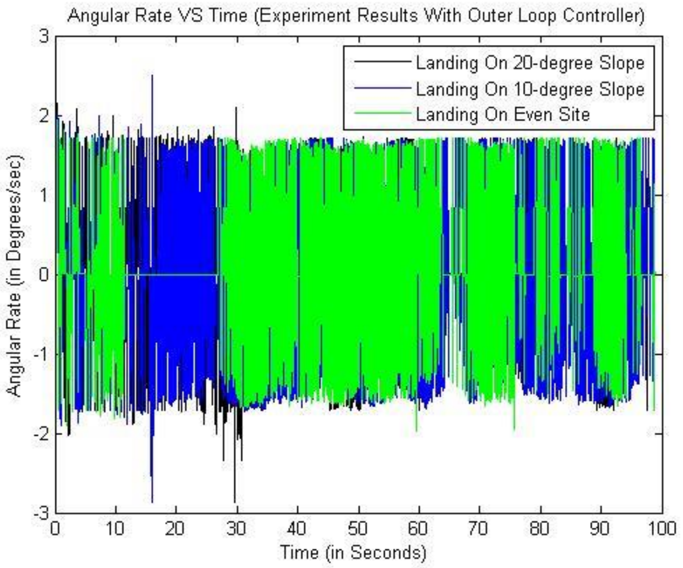

Figure 27 Angular Rate Results of Experiment

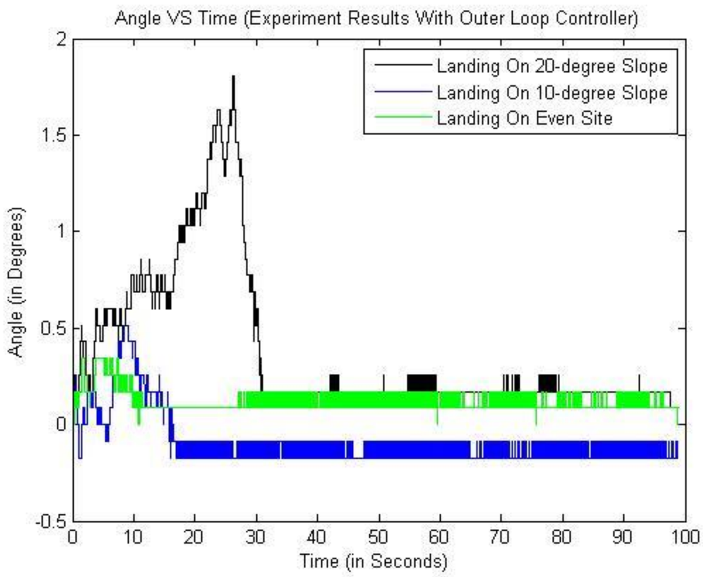

Figure 28 Angle Results of Experiment

The experiment is implemented by setting the quadrotor landing from *0.15 m* above the ground. The average landing speed is about *0.15 m/s*. The pitch angles are within 5 degrees and the pitch rate is around 0 with small fluctuations when the quadrotor descends to the even/uneven sites. The standard deviation in pitch angle is less than 1 degrees and the pitch rate fluctuate around 0 when the whole system is finally stable. The process of settling the quadrotor is slow and it commonly takes about 1 minute.

3) Experiment Results with Limited Sensing (Apply Control Structure in Fig. 22)

When the whole system is with limited sensing, we can assume the vehicle is roughly upright by driving the voltages to be the same. The experiment results in Fig. 29 & Fig. 30 & Fig. 31 show the performance of the control system with limited sensing.

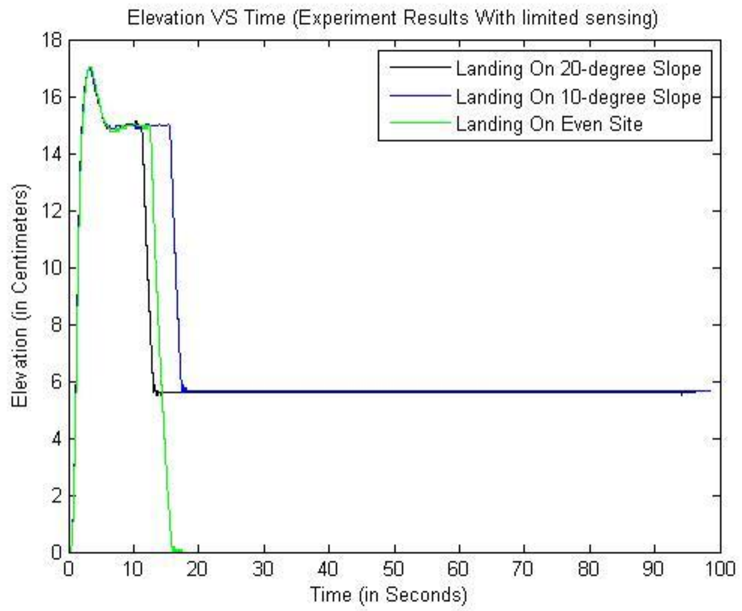

Figure 29 Elevation Results of Experiment

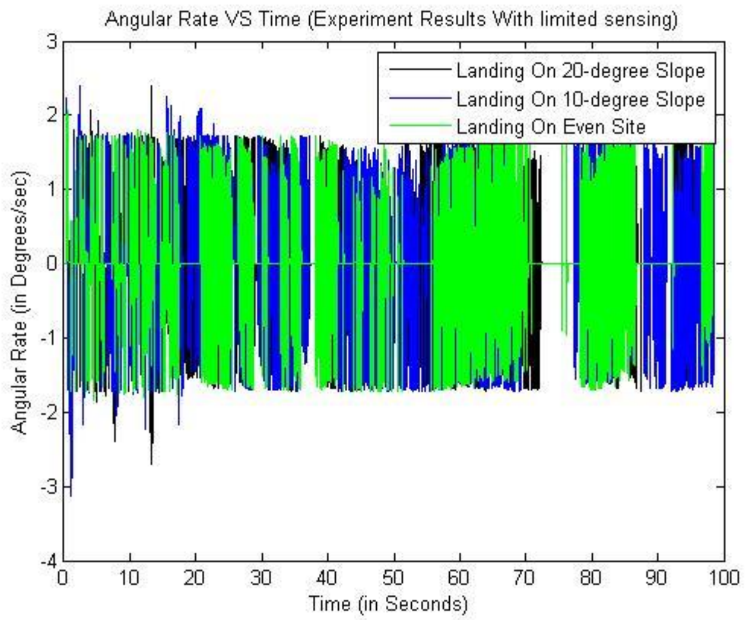

Figure 30 Angular Rate Results of Experiment

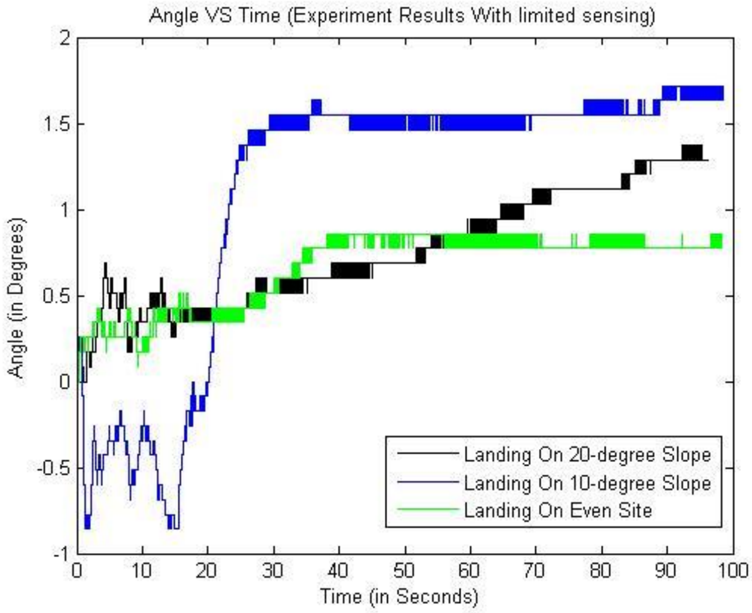

Figure 31 Angle Results of Experiment

The control system with limited sensing has little effect on the performance of angular rate. This is can be derived from Fig. 27 and Fig. 30. The pitch angles in Fig. 31 are greater than their values in Fig. 28. The controllers roughly rotate the vehicle to upright.

The parameters for the PID controller in the Perching Subsystem are not exactly the same values as in the simulation, but they have similarities and common characteristics. The values of Proportional gain and Integral gain of rate controller are very close to each other in both simulation and real test. The derivative gains are much smaller compared to Proportional gains or Integral gains. In angle controller, the final P gains are about 120 times smaller than those P gains in the rate controller on both simulation and real trial. One thing is different between simulation and real test parameters. In rate controller, the value of D gain is 10 times smaller than P/I gain during simulation, but the D gain in real test is 50 times smaller than P/I gain. This result is inferred by trials and errors. The motor will not rotate stably and reliably if the D gain is large. Instead, those motors will cause violent vibrations and thus cause the whole body beginning regularly quivering. D gain has to be small compared with P/I gains to overcome or avoid that situation.

All of these parameters in this test are derived by trials and errors for best performance. The proportional gain within angle controller is paid extra attention for precisely settling. If the P gain in angle controller is large, the controller will rotate vehicle fast. Then the quadrotor will possibly fall to the other side due to inertia. If this P gain is small, then this angle controller is nearly stopping settling. The best value for this P gain should be neither large nor small. The final parameters for these controllers are:

Rate Controller (inner loop): $K_p = 0.5, K_i = 0.5, K_d = 0.01, N(FiterCoefficient) = 100$

Angle Controller (outer loop): $K_p = 0.0027$

Fig. 32 shows the changes of motor voltages in 100 seconds. The two motor voltages are approximate 12 volts when the vehicle is hovering, and the voltages decrease to about 9 volts after landing. Therefore, the power is reduced when assuming motor's output power is proportional to the power supply voltage.

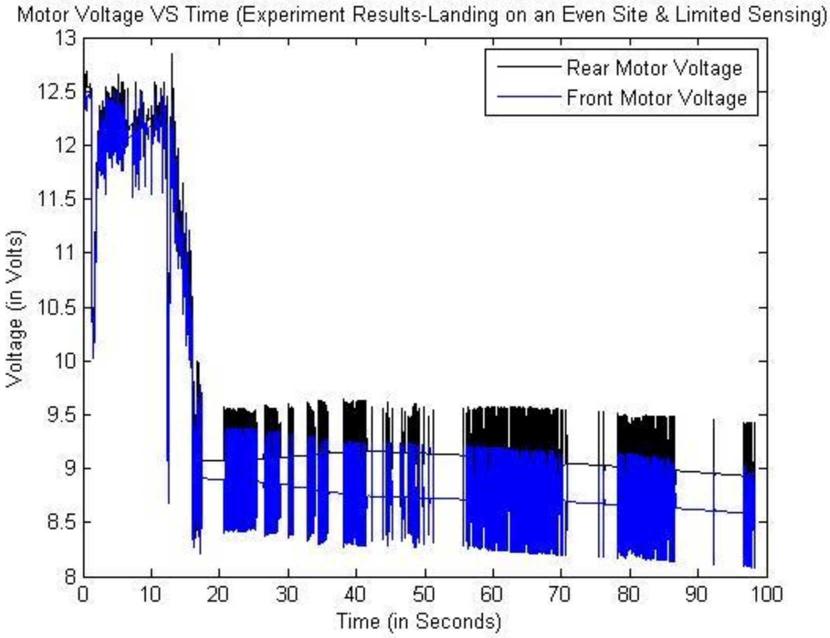

Figure 32 Voltage Results of Experiment

Fig. 33 shows that the one axis of experimental monopod perching quadrotor successfully landing on a slope and standing with reduced power.

Figure 33 Vehicle successfully landing on a slope

Videos of the experiments are available at: http://youtu.be/ctdlS2evQew.

The tests show that the control strategy works very well. The whole process is able to be automatically done by sending a 'land' signal. The tests also show that the quadrotor can easily and quickly take off from the leg. The total cost of sundries including the leg was less than 2 pound, while the Quanser was very expensive.

Conclusion

This report describes the structure of the monopod perching quadrotor and analyses its dynamic model. A one axis of experimental monopod perching quadrotor is designed and made which is based on Quanser 3-DOF helicopter. A modified PID controller is employed for landing Subsystem, which aims to land stably and reliably. A cascade scheme of PID control is employed for perching, which aims to rotate the body to upright. Simulation and experimental studies have been implemented to research the whole system.

The simulation results show that the Cascade Control System is able to robustly stabilize the quadrotor vehicle and rotate it to a vertically upright position very smoothly. The system response is fast and the steady-state error is zero when the initial tilt angle is within expected range. So the simulation verifies the effectiveness of the design of the control method.

The experiments discuss the research of landing and perching. The results show that the one axis of monopod perching quadrotor is able to rest on an even/uneven site at reduce power. When a 'landing' signal is sent, the vehicle will do the whole thing automatically, including a reliably landing on an even or uneven surface and then steadily achieving the attitude stabilization when given the appropriate PID parameters. The control system is also able to work with limited sensing. Tests also show that the quadrotor is able to take off quickly from the leg.

Acknowledgements

This work was supervised by Dr Arthur Richards. Dr Martin Pearson and Dr Guido Herrmann were second readers. Thank them for giving me guidance and suggestion.

Reference

[1] F. Zheng, W. Gao, "Adaptive integral backstepping control of a Micro-Quadrotor," *Intelligent Control and Information Processing (ICICIP), 2011 2nd International Conference*, vol.2, pp.910-915, 25-28 July 2011.

[2] S. Bouabdallah, "Design and control of quadrotors with application to autonomous flying," Ph.D. dissertation, EPFL, 2006.

[3] A. Tayebi, S. McGilvray, "Attitude Stabilization of a VTOL Quadrotor Aircraft," *IEEE Transactions on*, vol.14, no.3, pp.562-571, May 2006.

[4] B. Erginer, E. Altuğ, “Modeling and PD Control of a Quadrotor VTOL Vehicle,” *Intelligent Vehicles Symposium, 2007 IEEE*, pp.894-899, 13-15 June 2007.

[5] S.Bouabdallah, R. Siegwart, “Backstepping and Sliding-mode Techniques Applied to an Indoor Micro Quadrotor,” *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on*, pp.2247-2252, 18-22 April 2005.

[6] B. S. M. Henriques, “Estimation and Control of a Quadrotor Attitude,” M.S. dissertation, Dept. Mech. Eng., Tech. Univ. Lisbon, June, 2011.

[7] Q. Jiang, Y. Zeng, Q. Liu, et al, “Attitude and Heading Reference System for Quadrotor Based on MEMS Sensors,” *Instrumentation, Measurement, Computer, Communication and Control (IMCCC), 2012 Second International Conference on*, pp.1090-1093, 8-10 Dec. 2012.

[8] S.T. Pham, M.T Chew, "Sensor signal filtering in quadrotor control," *Sensors Applications Symposium (SAS), 2014 IEEE*, pp.293-298, 18-20 Feb. 2014.

[9] AL. Salih, M. Moghavvemi, H. Mohamed, et al, "Modelling and PID controller design for a quadrotor unmanned air vehicle," *Automation Quality and Testing Robotics (AQTR), 2010 IEEE International Conference on* , vol.1, pp.1,5, 28-30 May 2010.

[10] Learningace, “Lab 2 - DC motor-1st Order,” Learningace.com. [online] Available at: http://www.learningace.com/doc/1662949/874d65484925ca8048b146810a79cacd/lab-2-dc-motor-1st-order (Accessed: 5 Sep. 2014).

[11] OscarLiang.net, “How to choose Motor and Propeller for Quadcopter and Multicopter” - OscarLiang.net. [online] Available at: http://blog.oscarliang.net/how-to-choose-motor-and-propeller-for-quadcopter (Accessed: 5 Sep. 2014).

[12] Lokman. H, M. Moghavvemi, et al. “NNPID Controller for Induction Motors with Faults,” *Second International Conference on Control*, Instrumentation and Mechatronic Engineering (CIM09), June 2-3, 2009, pp. 548-552, 2009.

[13] Cog.yonsei.ac.kr, “IMU with Kalman filter and Kalman Filter Algorithm,” [online] Available at: http://cog.yonsei.ac.kr/quad/quad.htm (Accessed: 5 Sep. 2014).

[14] Mathworks, “Designing Cascade Control System with PI Controllers,” mathworks.co.uk. [online] Available at: http://www.mathworks.co.uk/help/control/examples/designing-cascade-control-system-with-pi-controllers.html (Accessed: 24 Aug. 2014).