University of Cincinnati

Date: 7/12/2013

I, Ruoyu Tan, hereby submit this original work as part of the requirements for the degree of Master of Science in Mechanical Engineering.

It is entitled:

Tracking of Ground Mobile Targets by Quadrotor Unmanned Aerial Vehicles

Student's name: **Ruoyu Tan**

This work and its defense approved by:

Committee chair: Manish Kumar, Ph.D.

Committee member: Kelly Cohen, Ph.D.

Committee member: David Thompson, Ph.D.

6744

Tracking of Ground Mobile Targets by Quadrotor Unmanned Aerial Vehicles

A thesis submitted to the
Graduate School
of the University of Cincinnati

in partial fulfillment of the
requirements of degree of

Master of Science

in the School of Dynamic Systems
College of Engineering and Applied Sciences
2013

by

Ruoyu Tan

Bachelor of Engineering (BE)
Central South University, 2010

Committee Chair: Dr. Manish Kumar

Abstract

An Unmanned Aerial Vehicle (UAV) is an aircraft without a human pilot on board. It can be controlled either autonomously by computers onboard, or using a remote control by a pilot on the ground, or in another vehicle. In both military and civilian sectors, UAVs are quickly obtaining popularity and expected to expand dramatically in the years to come. As UAVs gain more attention, one of the immediate requirements would be to have UAVs work as much autonomously as possible. One of the common tasks that UAVs would be engaged in is target tracking which has various potential applications in military field, law-enforcement, wildlife protection effort, and so on.

This thesis focuses on development of a controller for UAVs to track ground target. In particular, this thesis focuses on quadrotor UAV, which is a multicopter that is lifted and propelled using four motors. Admittedly, several target tracking control methods have been developed in recent years. However, only a few of them have been applied on a quadrotor. Most of these tracking methods, particularly those based on Proportional Derivative (PD) control laws, which have been applied on quadrotors, are not time efficient due to practical acceleration constraint and a number of parameters that need to be tuned. The UAV control problem can be divided into 4 sub-problems: Position Control, Motor Control, Trajectory Tracking and Trajectory Generation. In this thesis, the dynamic equations of motion for quadrotors and a Proportional Derivative control law is derived to solve the problems of Position Control, Motor Control and Trajectory Tracking. A Proportional Navigation (PN) based switching strategy is proposed to address the problem of Trajectory Generation. The

experiments and numerical simulations are performed using non-maneuvering and maneuvering targets. The simulation results show that the proposed PN based switching strategy not only carries out effective tracking but also results into smaller oscillations and errors when compared to the widely used PD tracking method.

The switching strategy, as proposed as a solution to target tracking problem, leaves an important question with regard to when should the switching happen. It is intuitive that the time of switching will play a role in how fast the UAV converges to the target. The second problem considered in this thesis relates to the optimal time of switching that would minimize the positional error between the UAV and the target. An optimal switching strategy is proposed to obtain the optimal switching time for both non-maneuvering and maneuvering targets. Analytical solutions that generate trajectories based on PN and PD methods are used in this strategy. The numerical simulations validate the optimality, reliability, and accuracy of the proposed method for both non-maneuvering and maneuvering targets.

Acknowledgements

I wish to thank my advisor, Dr. Manish Kumar, for his support, encouragement and guidance through my graduate studies. His technical insight usually showed me right way to solve the tricky problems. His exemplary personality has made my graduate research fruitful and enjoyable. Thanks are also due for his input and feedback on this work. I am extremely fortunate to have him as an advisor.

I would like to thank Dr. David Thompson. It is because of his creative guidance that I was inspired to begin this work in this research direction.

I also thank Dr. Kelly Cohen and Dr. Ali Minai for their input through the course works and their invaluable help as my referees.

Thanks to Baba and Mama. They receive my deepest gratitude and love for their dedication and the many years of constant love and encouragement that provided the foundation for this work.

Special thanks to Balaji Sharma for helping me at various stages of this work. He is a very good friend, an esteemed mentor, and an excellent student leader of the CDS lab. Thanks also to Baisravan HomChaudhuri, my current roommate. His input in reviewing and refining this work are instructive and priceless. I am grateful for his cooking in the kitchen and the flavor of curry always lifted me up when I was too tired to work.

I am indebted to Yan Zhuang, a student of Huazhong University of Science and Technology, Tim Arnett, a student of University of Cincinnati and Glen Lichtwark

with University of Queensland for their technical support in setting up the CDS quadrotor testbed.

The CDS lab has always been a friendly research environment. I would like to thank my colleagues, Benson Issac, Gaurav Mukherjee, Bipin Shedge and Sushil Garg, for their good-natured attitude.

Contents

1	Introduction	1
1.1	Problem Motivation	2
1.2	Target Tracking Problem	4
1.3	Document Outlines	5
2	Literature Review	7
2.1	Quadrotor System Testbeds	8
2.2	Schematic of Guidance and Control Architecture for UAVs	9
2.3	Existing Tracking Methods	11
2.4	Existing Proportional Navigation Methods	13
2.5	Optimal Switching Strategy in Robotics Research	15
3	Problem Description	18

3.1	Target Tracking (Problem 1)	18
3.2	Optimal Switching Time (Problem 2)	20
4	Quadrotor Dynamics	22
4.1	Dynamic Model and Position Control	22
4.2	Motor Control	25
5	PN Based Switched Tracking Strategy	27
5.1	PD Based Trajectory Generation	28
5.2	PN Based Trajectory Generation	28
5.3	Simulation Results	34
5.4	Experimental Results	38
5.4.1	Experimental Facilities	39
5.4.2	Schematic of Experimental Setup	42
5.4.3	Experimental Results	44
6	Optimal Switching Strategy for Non-maneuvering target	48
6.1	Theoretical Analysis	49
6.2	Simulation Results	56

7	Optimal Switching Strategy for Maneuvering Target	63
7.1	Theoretical Analysis	63
7.2	Simulation Results	65
8	Conclusions and Scope for Future Work	71
8.1	Conclusions	71
8.2	Contributions	73
8.3	Scope for Future Work	73

List of Figures

1.1	Pelican Quadrotor by Ascending Technologies	3
2.1	Schematic of Guidance and Control Architecture for UAVs	10
3.1	Schematic of Proposed Method to Solve Problem 1	19
4.1	Schematic of Guidance and Control Architecture for UAVs	23
5.1	Schematic Show in Different Variables Used in the Guidance Laws . .	30
5.2	Phase Plot Showing a Comparison of PN and PD to Track a Target with Constant Velocity	31
5.3	Different Scenarios to Compare IPN, RTPN, NGL and PPN	33
5.4	Plot Comparing the Convergence Time for IPN and IGL	34
5.5	Case 1 Simulation Study.	36
5.6	Case 2 Simulation Study.	37

5.7	Case 3 Simulation Study.	38
5.8	Parrot AR. Drone 1.0 Quadrotor	40
5.9	K-team Corperation Khepera III	40
5.10	Experimental Screen Shot	41
5.11	Schematic of Experimental Setup	42
5.12	Calibration Process Showing Trajectory of Calibration Wand	43
5.13	Project File Establishment	43
5.14	Experimental Results for 2 Cases with Pelican UAV.	45
5.15	The UAV and the Target Trajectory in 3D for Case 1	46
5.16	Experimental Results for 2 Cases with Parrot Drone UAV.	47
6.1	Planar Tracking Geometry	51
6.2	Simulation Results for Case 1 ($\lambda = 2$)	58
6.3	Simulation Results for Case 2 ($\lambda = 2$)	58
6.4	Simulation Results for Case 3 ($\lambda = 2$)	59
6.5	Simulation Results for Case 4 ($\lambda = 2$)	59
6.6	Simulation Results for Case 1 ($\lambda = 1$)	61
6.7	Simulation Results for Case 2 ($\lambda = 1$)	61

6.8	Simulation Results for Case 3 ($\lambda = 1$)	62
6.9	Simulation Results for Case 4 ($\lambda = 1$)	62
7.1	Simulation Results for Case 1 ($\lambda = 2$).	67
7.2	Simulation Results for Case 2 ($\lambda = 2$).	67
7.3	Simulation Results for Case 3 ($\lambda = 2$).	68
7.4	Simulation Results for Case 1 ($\lambda = 1$).	69
7.5	Simulation Results for Case 2 ($\lambda = 1$).	70
7.6	Simulation Results for Case 3 ($\lambda = 1$).	70

List of Tables

5.1	Convergence Time for IPN, RTPN, PPN AND NGL in Case 1	33
5.2	Convergence Time for IPN, RTPN, PPN AND NGL in Case 2	33
5.3	Convergence Time for IPN, RTPN, PPN AND NGL in Case 3	34

Chapter 1

Introduction

Unmanned Aerial Vehicles (UAVs), or drones as they are popularly known, have seen a lot of interest recently due to their military applications. The impending regulations to allow UAVs in the US airspace open up enormous possibility of applications of UAVs in civilian domains. For example, the UAVs can be used for gathering data in large-scale disasters or be used for law enforcement activities. One of the common tasks that UAVs would be engaged in is tracking of mobile ground targets. This thesis focuses on development of controller for UAVs to track ground target. There are a wide range of UAVs with different shapes, sizes, configurations, and characteristics. Some of the existing UAVS are Coax Micro Helicopter, Multi-rotors UAV, and fixed wing UAV. The UAV considered in this thesis is of quadrotor type, a multicopter that is lifted and propelled using four rotors. Though a lot of target tracking control methods exists recently, only a few of them have been applied on quadrotors. Most of these tracking methods, particularly those based on Proportional Derivative (PD)

control laws, fail to provide time efficiency of tracking due to the constraints on acceleration, limit of UAV rotors, and a number of parameters that need to be tuned. In this context, the objective of this thesis can be stated as “the development of time-efficient tracking methods for both non-maneuvering and maneuvering ground target”

1.1 Problem Motivation

The thesis’ work has been motivated by the overwhelming UAV applications in scientific and military fields, which results from the advances in communication, computing, sensing, solid state devices, and battery technology. With the use of on-board sensors, this technology is able to provide a feasible solution for low-altitude and high-resolution applications such as scientific data gathering, homeland security, search, and rescue, precision agriculture, forest fire monitoring, geological research and military reconnaissance. Besides, the public tend to strongly support the use of UAV, according to a national study [1].

Most of current UAV applications are conducted using fixed-wing UAVs and dual-rotor helicopters. There is a lot of interest recently on quadrotor UAVs. Quadrotor (Figure 1.1) is a type of UAV which consists of four rotors in total, with two pairs of counter-rotating, fixed-pitch blades located at the four corners of the aircraft. The interest of the research community can be due to advantages against comparable vertical take off and landing (VTOL) UAVs [2].

First, the quadrotor relies on fixed pitch rotors and uses variation in motor speed

Figure 1.1: Pelican Quadrotor by Ascending Technologies

for vehicle control instead of complex mechanical control linkage for rotor actuation. As a result, both the design and maintenance of the vehicle are simplified.

Second, the use of four rotors enable the reduction of individual rotor diameter. Thus it reduces the risk of collision with the obstacle for the individual rotors.

Furthermore, through shortening the distance between the rotors and the frame, the rotors are protected from damage during collisions in indoors and in obstacle-dense environments. These are helpful for inexperienced pilots to in carrying out indoor test flights.

Specifically, compared to fixed wing UAVs, the quadrotor provides advantages in terms of relaxed constraints for turning rate and due to their applicability for indoor and tight environments. The quadrotor is also easy to control compared to a helicopter whose tail rotor control is more challenging.

1.2 Target Tracking Problem

Target Tracking Problem is a topic of much interest in UAV research. The use of object tracking is important in the task of:

(i) motion-based recognition: human identification based on gait, automatic object detection, etc;

(ii) automated surveillance: monitoring a scene to detect suspicious activities or unlikely events;

(iii) video indexing: automatic annotation and retrieval of the videos in multimedia databases;

(iv) human-computer interaction: gesture recognition, eye gaze tracking for data input to computer;

(v) traffic monitoring: real-time gathering of traffic statistics to direct traffic flow.

(vi) vehicle navigation: video-based path planning and obstacle avoidance capabilities.

UAV target tracking problem has many applications in various fields [3]. In a military scenario, UAVs can be used to track an enemy or escort a friendly convoy while avoiding no-fly zones and possible sites of surface-to-air missiles (SAMs). In border patrol application, UAVs can be controlled to track intruders while staying within the border and avoiding high elevation. In a law-enforcement scenario, criminals might be pursued or a specific vehicle might be tracked for protection while avoiding high buildings or residential areas. As a wildlife protection effort, animals can be tracked

to understand their natural habitat.

The difficulties in tracking objects result from a number of factors:

- (i) fast maneuvers of the targets;
- (ii) noise in images and communication between camera and receiver;
- (iii) multiple tasks switching such as obstacle avoidance while tracking a target;
- (iv) the requirement for following target after UAV comes close to target;
- (v) real-time data processing.

1.3 Document Outlines

The outline of this documents is provided below:

Chapter 1 In this chapter, an introduction of this research is presented. The motivation of the UAV research, and especially, the application of quadrotor UAVs are discussed. In addition, the applications and challenges of UAV target tracking problem have been proposed.

Chapter 2 The background survey and the related works are provided in this chapter.

Chapter 3 In this chapter, the two main problems, that have been being addressed in this thesis, are described. The solutions for these problems are briefly introduced.

Chapter 4 The dynamic equations of the quadrotors are obtained by using Newton-Euler equation in this chapter. A Proportional Derivative (PD) control law is derived for position and attitude control of the quadrotor.

Chapter 5 This chapter introduces a Proportional Navigation (PN) based tracking strategy to solve the first problem presented in Chapter 3. The existing PN based tracking methods have been compared and Ideal Proportional Navigation method is found to its accommodate for our quadrotor dynamics better than other methods. Subsequently, the proposed tracking method has been applied in simulation and experiment.

Chapter 6 In this chapter, an optimal switching strategy is proposed to solve the second problem presented in Chapter 3 for non-maneuvering target. Several simulations have been performed to test the accuracy and reliability of this strategy.

Chapter 7 In this chapter, an optimal switching strategy is proposed to solve the second problem presented in Chapter 3 for maneuvering target. Several simulations have been performed to test the accuracy and reliability of this strategy.

Chapter 8 The conclusions and the contributions of the thesis are provided in this chapter and the future scope of this research is discussed.

Chapter 2

Literature Review

This chapter presents the background survey of the existing literature related to quadrotor UAV tracking problem. Several quadrotor system testbeds and their control techniques are introduced and a five-layer hierarchical structure is also provided, which is used for UAV guidance and control. Existing tracking methods have been proposed and compared with Proportional Navigation (PN) method for quadrotor control. The comparison shows that the PN tracking method has potential to be applied on quadrotor control and results in a time efficient tracking result. Subsequently, features and research progress of existing Proportional Navigation methods have been discussed. In this thesis, a switching mechanism has been used to change the tracking method from PN to PD form. Several research works on optimal switching strategy for robot control have been presented.

2.1 Quadrotor System Testbeds

Quadrotors have become very popular recently among researchers engaged in aerial robots and a lot of work has been carried out to develop methods to control them.

Several testbeds have controlled the quadrotor with external tethers and stabilization devices. One testbed [4] consisted of HMX-4 quadrotor, which was 1.5 pound in mass and 76cm in length between rotor tips and had about 3 minute flight time. The quadrotor was flown with the gyro augmentation system included with the vehicle active, and with X-Y motion constraints. Altitude and yaw control were implemented using feedback linearized attitude control. Backstepping control was applied for quadrotor position control, while state estimation was accomplished with an off-board computer vision system. Another testbed [5] relied on a tether to use a POLYHEMUS magnetic positioning system. Tight position control at slow speeds was demonstrated using a nonlinear control technique based on nested saturation for lateral control with linearized equations of motion, and compensating in altitude control for the tilt of thrust vectors.

There also have been development of testbeds that have relied on various nonlinear control techniques without a tether. One well known testbed [6], based on the AscTec Hummingbird quadrotor, made use of PD control for both attitude and position control. The Hummingbird had a tip-to-tip wingspan of 55 cm, a height of 8 cm, and a weight of about 500 g including a battery. The testbed in [2] utilized PD control law for the control of STARMAC II, a type of quadrotor. The STARMAC quadrotors were custom-built vehicles, 0.75 m in length on each side of UAV, weighing 1.1 kg to

1.5 kg depending on the computing configuration, with an additional payload capacity of roughly 1 kg above the base weight. Similarly, X-4 FLYER project [7], proposed a controller based on saturating the linear dynamics for bounding the vehicle orientation and limiting it to very small values. Its control strategy was based on Lyapunov function concept that used backstepping techniques. Furthermore, another project [8] presented a nonlinear control algorithm for a mini-rotorcraft with four rotors. In this project, the dynamic model of the rotorcraft was obtained using an Euler-Lagrange approach and a control strategy based on a nested saturation was proposed so that the control input satisfies some given amplitude constraints.

Several vehicles saw success using Linear Quadratic Regulator (LQR) controllers on linearized dynamic models. The Cornell Autonomous Flying Vehicle (AFV) [9] was a custom airframe with brushless motors controlled by custom circuitry to improve resolution. Position control was accomplished using dead-reckoning estimation, with a human input for zero integration error.

2.2 Schematic of Guidance and Control Architecture for UAVs

Usually, the overall control of the UAV is achieved in a hierarchical fashion as shown in the schematic in Figure 2.1 [10]. The schematic has five layers: Path Planning, Trajectory Optimization, Trajectory Tracking, Position Control and Motor control. Path planning layer provides waypoints based on the knowledge of entire map and overall objective of the aircraft. Once these waypoints are obtained, an available,

Figure 2.1: Schematic of Guidance and Control Architecture for UAVs

shortest, and smooth trajectory (that complies with the UAV constraints) is obtained at the trajectory optimization layer. Then, a tracking algorithm enables the UAV to follow the desired trajectory by providing desired positional values and values of lateral and vertical acceleration. Position Control layer is necessary to calculate the commands that satisfy the relationship between position and altitude based on UAV dynamics. Position Control, hence, provides the lower level control inputs including altitude, pitch, yaw, and thrust. Finally, Motor Control layer is implemented to satisfy the relationship between motor dynamics and UAV dynamics to provide motor controls such as rotor speeds.

A lot of research has been reported in literature to carry out the tasks in different layers. For example, in the Path Planning layer, authors in [11] develop a switching strategy between two flight trajectories for fixed-wing UAV based on the speed relationship with UAV and target. Work reported in [12] provides a Pseudo

Control Hedging method which combines inner loop in the Position Control layer and outer loop in the Trajectory Tracking layer which can use the same adaptive element to cancel model errors on autonomous unmanned helicopter. Similarly, in another study [13] a fuzzy logic based control is applied in the Position Control layer. Control Lyapunov Function (CLF) is derived in [14] to provide feasible control and optimize auxiliary performance function in the Trajectory Tracking layer. A back stepping controller which seeks a desired position with a desired heading for the UAV rotorcrafts is presented for the Position Control layer in [15] .

2.3 Existing Tracking Methods

Proportional navigation (PN) is a well-known guidance method which has been traditionally applied as a missile guidance method to enable a missile catch its target in optimal time [16]. This method tries to achieve a constant bearing approach that is based on the fact that the missile will always collide with the target in a time-optimal fashion as long as the angle representing the line of sight (LOS) of the missile in the direction of the target (LOS angle) is kept constant. The PN approach modifies the constant bearing approach to accommodate for maneuvering targets by accelerating the missile in a direction lateral to the LOS angle and with magnitude proportional to the rate of change of the LOS angle. In target tracking problem, its advantage is that the PN method results in optimization of path when the distance between the UAV and target is large.

Admittedly, several tracking methods which have potential to be applied for

quadrotor control have been developed in literature. Here, we compare the relative advantages and disadvantages of the PN strategy with respect to the other methods in literature.

One approach for UAV based target tracking can be simply implemented by replacing waypoints of the trajectory by real-time position of target. The strategy for doing this, which is quite popular for implementing, is the Proportional Derivative (PD) based control. PD based method for trajectory tracking has been widely used on quad-rotors [6], [17]. One of the major issues with PD control is with respect to tuning of its parameters that would provide optimal results. Specifically, when relative distance and/or relative velocity between UAV and target vary by a large amount, no single set of parameters would provide a good performance. Other works on trajectory tracking such as [12] and [13] propose fuzzy-logic based method and Neural Networks respectively.

The authors in [18] propose a guidance law in which a virtual target is defined to enable a UAV track it at a constant distance. In this paper, a suitable Lyapunov function is used for designing the control law. Although simulation results show its robustness to disturbances, it uses a number of parameters that require tuning. Similarly, a direct adaptive control is used in [19] to track a reference system of target trajectory, but still uses a virtual target. These works, however, do not focus on the time-optimality issue required for tracking maneuvering or evading targets.

The authors in [20] have proposed a hybrid method including a modified PN and angular acceleration guidance (AAG) which should perform better when target has non-constant acceleration. However, the gain which is designed for switching PN to

AAG is obtained via prediction of target maneuver. In the real application, to carry out such prediction for an erratically maneuvering target is not possible.

A new nonlinear guidance logic law for trajectory tracking is proposed in [21], which is demonstrated to have a better performance than traditional linear technique for curved trajectories. The authors in [22] have applied this method on fixed wing UAV to yield a good visibility ratio in poor sideways visibility condition. However, its performance to track straight moving target is demonstrated to be the same as a PD controller.

In addition, a proportional navigation guidance based technique [23] has been used for interception of object using robotic manipulator. A switching strategy also has been implemented to switch the PN based guidance into a PD-type controller. Its robustness and computational efficiency are shown via several simulation studies in that paper.

2.4 Existing Proportional Navigation Methods

Proportional navigation has attracted a great deal of interest in the missile guidance literature since its inception in 1940s because of its simplicity of implementation. The PN schemes can be categorized into two classes, one is the line-of-sight (LOS) reference such as the true proportional navigation (TPN) [24], generalized true proportional navigation (GTPN) [25], realistic true proportional navigation (RTPN) [26] and ideal proportional navigation (IPN) [27], another is interceptor velocity referenced class such as pure proportional navigation (PPN) [28]. The former is preferred as compared

to the latter due to its mathematical tractability but the PPN is believed to be more practically implementable with no requirements on forward acceleration and with no constraints on the initial engagement [29].

In TPN, the commanded acceleration is applied in a direction normal to the interceptor-target line of sight. Authors in [24] provide a closed-form solution of the equation of motion of an ideal missile pursuing a non-maneuvering target. The capture region of TPN is solved analytically in [30] with a maneuvering target which is assumed to maneuver in a way to increase the LOS rate and thus oppose PN philosophy of annulling the LOS rate.

GTPN is defined as similar to TPN, except that the interceptor acceleration is not necessarily applied normal to LOS. Authors in [25] gives a closed form solution of the equation of motion of an ideal missile pursuing a non-maneuvering target under navigation of GTPN. In addition, authors in [31] derives and complete closed-form solution of GTPN with a maneuvering target. The capture regions of GTPN guidance laws are obtained through a rigorous qualitative analysis [32].

Compared to TPN, the closing speed constant in the command acceleration equation is replaced by the rate of range-to-go between the interceptor and target in RTPN. Analytical solution of RTPN is proposed for both maneuvering and non-maneuvering targets in [30]. The capture region of RTPN is solved analytically in [33] against a maneuvering target where the assumption of constant closing velocity used in the guidance law is relaxed.

In IPN, the commanded acceleration is applied in a direction normal to the relative velocity between the interceptor and the target. The closed-form solutions of IPN are

derived for maneuvering and non-maneuvering targets in [27].

Similarly, the closed-form solutions of PPN are completely derived for maneuvering targets in [26] and [28]. In [34], a qualitative analysis of the trajectories of an interceptor pursuing a maneuvering target is presented.

Augmented proportional navigation (APN) [16] is a linearized version of RTPN for the maneuvering target. Since APN makes use of extra information, namely, knowledge of the target maneuver, it is reasonable that this knowledge should enable the missile to maneuver in a more efficient manner with less requirement of total acceleration.

A Nonlinear Guidance Law (NGL) is proposed in [35]. The method uses inertial speed in the computation of commanded lateral acceleration and adds adaptive capability enabling to the change of vehicle speed in response to external disturbances, such as wind. The simulation results showing its better performance is also presented.

2.5 Optimal Switching Strategy in Robotics Research

Several robotic applications require the controller to change its form to accommodate change in environment or change in the system's task.

A logic-based switching control is used to switch controllers for a 3-Degree of Freedom (DOF) planar manipulator under end-effector trajectory tracking in [36]. It is demonstrated to enhance the stability and performance for this class of manipulators.

For the robot to efficiently tackle unwanted local trapping and oscillation in navigation of an intelligent target, a real/virtual target switching strategy is proposed in [37]. Simulation and experimental results have been provided to support the method.

When a robot is pursuing a target, an obstacle avoidance task should be completed at the same time. Authors in [38] proposes a hierarchical switching strategy to determine whether the mobile robot should perform obstacle avoidance or target tracking using vision information only.

In [11], two classes of flight trajectories are proposed for tracking ground moving target with a UAV. An optimal switching point based on velocity ratio between the UAV and the target is used as a switching criterion between these trajectories. Also authors in [39] have discussed a switching based control strategy for UAV target tracking problem using range-only measurement. A continuous cycle of two distinct phases have been introduced in this paper, one is following the bearing and another is repeating the previous step when the range is decreasing.

Due to the change of environment or change of tasks, UAVs have to change their flight formation in many cases. Three kinds of conventional formation of switching strategy and switching control law are introduced in [40].

A proportional navigation guidance based technique [23] has been used for interception of an object using robotic manipulator. A switching strategy also has been implemented to switch the PN based guidance into a PD-type controller. Its robustness and computational efficiency are shown via several simulation studies. But this work only provides a numerical study which is hard to implement in application. Also,

this work considers the robot manipulator dynamics instead of quadrotor dynamics, and also the interception problem instead of target tracking problem.

Chapter 3

Problem Description

In this chapter, two main problems that are being addressed in this thesis are described. The first problem is developing control laws for quadrotor to track ground moving target. The control is achieved in 4 layers (as shown in Figure 3.1): Trajectory Generation, Trajectory Tracking, Position Control, and Motor Control. The second problem is obtaining the optimal switching time of switching strategy which is developed to solve Problem 1. To handle this problem, an optimal switching strategy based on an analytical formulation for both non-maneuvering and maneuvering targets will be proposed.

3.1 Target Tracking (Problem 1)

This thesis focuses on developing control laws for a quadrotor to track a ground moving target. Target's position can be defined as $U_T \in R^2$. The UAV's real time

position can be represented as $U \in R^3$. The position error of the UAV with respect to the target is given by:

$$e = \sqrt{(U_{Tx} - U_x)^2 + (U_{Ty} - U_y)^2} \quad (3.1)$$

The objective of the controller is to reduce the position error to zero.

Figure 3.1: Schematic of Proposed Method to Solve Problem 1

Our approach to solve the Problem 1 can be represented as the guidance and control architecture for UAV as shown in Figure 3.1. In the Trajectory Generation layer, the desired trajectory is developed and the desired acceleration command given by $\ddot{U}^{des}$, is obtained from our proposed PN based tracking method which will be discussed in chapter 5. The Trajectory Tracking, Position Control and Motor Control layer will be discussed in chapter 4.

One point to be noted here is that proportional navigation based guidance meth-

ods were designed originally for missile guidance problem where the objective is the interception of missiles. For target tracking problem, the objective is to track a particular object and thus try to keep the tracking error small for the entire flight duration. When UAV reaches close to the target, the Line of Sight (LOS) angle is subjected to larger variations which result in the increase of the distance between the quadrotor and the target. Thus it negatively influences the tracking efficiency even makes the quadrotor lose its target. To overcome this problem, we propose to switch PN tracking method to the widely used PD tracking method before this problem happens. To be specific, once the UAV comes within a specified distance of the target, a switching strategy for switching from PN to PD is implemented.

3.2 Optimal Switching Time (Problem 2)

As explained above, the PN based navigation method needs to switch to PD law in order to accommodate for the objective of target tracking. Now, the switching strategy as proposed as a solution to Problem 1 leaves an important question with regard to when should the switching take place. It is intuitive that the time of switching will play a role in how fast the UAV converges to the target. The second problem considered in this thesis relates to the optimal time of switching that would minimize the positional error between the UAV and the target.

The problem can be formulated as follows. Let us define the total time during which the UAV is controlled by PN and PD law as t_{PN} and t_{PD} respectively, such that the total time for entire motion is given by $t_f = t_{PN} + t_{PD}$. Hence, the UAV

starts at time $t = 0$ governed by PN control law and switches to PD control law at time $t = t_{PN}$. The objective of the problem is to determine the value of TPN, i.e., the time at which switching occurs, so that the positional error given by Equation (3.1) at t_f is minimized.

To solve the problem 2, an optimal switching strategy for both non-maneuvering and maneuvering targets will be presented in Chapter 6 and Chapter 7. It is based on the analytical solution of PN and PD tracking law.

Chapter 4

Quadrotor Dynamics

This chapter consists of quadrotor dynamic model as well as the approach for Problem 1 on Trajectory Tracking, Position Control and Motor Control layers. A quadrotor dynamic model and its motor dynamics are introduced. Besides, a Proportional Derivative control law is derived for position and attitude control of the quadrotors.

4.1 Dynamic Model and Position Control

Quadrotor is a type of UAV which is lifted and propelled using four rotors placed at the four diagonally opposite ends of the UAV. The rotor angular velocities are used as four inputs to the system to control the three translation and three rotational degrees of freedom. The motion and the dynamics of the quadrotor can be studied with the help of two coordinate systems: the world frame (W) and the body frame (B). The coordinate systems and the free body diagram of quadrotor are shown in Figure 4.1.

Figure 4.1: Schematic of Guidance and Control Architecture for UAVs

In Figure 4.1, the world frame W is determined by axes X_w, Y_w, Z_w . The body frame is attached to the center of mass of the quadrotor. Let us define forward direction as positive X_B direction pointing from the center of mass to rotor 1. Rotor 2 is in the positive direction of the Y_B axis and rotor 3 is in the negative of the Y_B axis. Z_B direction is perpendicular to the X_B, Y_B plane. We use Z-X-Y Euler angle to model the rotation of the quadrotor in the world frame. To get frame (B) coordinates from frame (W), we first rotate by angle ψ (yaw) along the Z_w , then rotate by angle ϕ (roll) along the intermediate X-axis, and then finally rotate by angle θ (pitch) along the intermediate Y-axis. Thus the rotation matrix for a vector from frame (B) to frame (W) is given by

$$R = \begin{bmatrix} c\psi c\theta - s\phi s\psi s\theta & -c\phi s\psi & c\psi s\theta + c\theta s\phi s\psi \\ c\theta s\psi + c\psi s\phi s\theta & c\phi s\psi & s\psi s\theta - c\psi c\theta s\phi \\ -c\phi s\theta & s\phi & c\phi c\theta \end{bmatrix} \quad (4.1)$$

According to the Newton's second law, the position control of quadrotor in world frame $\ddot{U}$ (U is the position of the quadrotor), can be obtained from:

$$m\ddot{U} = \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix} + R \begin{bmatrix} 0 \\ 0 \\ \sum F_i \end{bmatrix} \quad (4.2)$$

where m is the mass of the quadrotor, g is the acceleration due to gravity, F_i is the force from each rotor i . Each rotor i will produce F_i and a moment M_i given by:

$$F_i = k_F w_i^2 \quad M_i = k_M w_i^2 \quad (4.3)$$

where w_i is the rotational speed of each rotor i , k_F, k_M are constants.

Relationship between the angular acceleration, force and moments can be obtained by Euler equation:

$$I \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} L(F_2 - F_4) \\ L(F_3 - F_1) \\ M_1 - M_2 + M_3 - M_4 \end{bmatrix} - \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times I \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (4.4)$$

where p, q and r are the rates of roll, pitch, yaw angles respectively. L is the distance from the axis of rotors to the center of the quadrotor. I is the inertia matrix of quadrotor.

4.2 Motor Control

The inputs to the quadrotors are the rotational speeds of the four rotors and are given as:

$$\begin{bmatrix} w_1^{des} \\ w_2^{des} \\ w_3^{des} \\ w_4^{des} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -1 & 1 \\ 1 & 1 & 0 & -1 \\ 1 & 0 & 1 & 1 \\ 1 & -1 & 0 & -1 \end{bmatrix} \begin{bmatrix} w_h + \Delta w_F \\ \Delta w_\phi \\ \Delta w_\theta \\ \Delta w_\psi \end{bmatrix} \quad (4.5)$$

where the nominal speed of each rotor required for hovering in steady state is w_h , the deviations from the nominal vector Δw_F provide a net force in Z_B direction. The other deviations: $\Delta w_\phi, \Delta w_\theta, \Delta w_\psi$, produce forces and moments which result in moments causing motions in roll, pitch, and yaw respectively. This is similar to the approach described in [6].

The components of angular velocity of the robot in the body frame are p, q and r. Close to the nominal hover state, they are considered to be equal to the derivatives of the roll, pitch, and yaw angles: $\dot{\phi}, \dot{\theta}, \dot{\psi}$. Above deviations can be obtained by PD control laws based on desired values of roll, pitch, and yaw:

$$\begin{aligned}
\Delta w_\phi &= k_{p,\phi} (\phi^{des} - \phi) + k_{d,\phi} (p^{des} - p) \\
\Delta w_\theta &= k_{p,\theta} (\theta^{des} - \theta) + k_{d,\theta} (q^{des} - q) \\
\Delta w_\psi &= k_{p,\psi} (\psi^{des} - \psi) + k_{d,\psi} (r^{des} - r) \\
w_h + \Delta w_f &= \sqrt{\frac{m}{16k_f g}} \ddot{u}_y^{des} + \sqrt{\frac{mg}{4k_f}}
\end{aligned} \tag{4.6}$$

In Equation (4.6), the desired acceleration command can be transferred to the desired roll, pitch angular velocity as:

$$\begin{aligned}
\phi^{des} &= \frac{1}{g} \left(\ddot{U}_x^{des} \sin\psi_T - \ddot{U}_y^{des} \cos\psi_T \right) \\
\theta^{des} &= \frac{1}{g} \left(\ddot{U}_x^{des} \cos\psi_T + \ddot{U}_y^{des} \sin\psi_T \right)
\end{aligned} \tag{4.7}$$

$\ddot{U}_x^{des}, \ddot{U}_y^{des}$ are desired acceleration commands in X, Y directions respectively (obtained using the trajectory generation method discussed next). In this case, quadrotor is required to keep the same altitude, so $\ddot{U}_z^{des}$ is kept zero while tracking.

Chapter 5

PN Based Switched Tracking Strategy

This chapter introduces a PN based switched tracking strategy to solve Problem 1 in Chapter 3. The purpose of strategy is generating an time efficient trajectory for quadrotor. Existing PN based tracking methods have been compared in different scenarios and Ideal Proportional Navigation(IPN) is shown to perform well for quadrotor dynamics. Subsequently, the proposed tracking strategy has been applied in simulation and experiment. Simulation results show our switched tracking strategy's stability and efficiency. On the other hand, an experimental environment for quadrotor research has been established and the proposed switched tracking strategy is applied in experiment.

5.1 PD Based Trajectory Generation

A PD control tracking method tries to reduce the error between the positions of the UAV and the target. The desired accelerations in X and Y directions and obtained from PD law are given by Equation [6] :

$$\ddot{\vec{u}}^{des} = \ddot{\vec{u}}_T + k_d \left(\dot{\vec{u}}_T - \dot{\vec{u}} \right) + k_p (\vec{u}_T - \vec{u}) \quad (5.1)$$

where $\vec{u}_T, \dot{\vec{u}}_T, \ddot{\vec{u}}_T \in R^2$ are target's position, velocity and acceleration, $\vec{u}, \dot{\vec{u}}, \ddot{\vec{u}} \in R^2$ are UAV's position, velocity and acceleration. It may be noted that $\vec{u} = [U_x, U_y]$, where U is defined in Chapter 3.

5.2 PN Based Trajectory Generation

To choose an appropriate type of proportional navigation strategy suitable for our application, RTPN, IPN, PPN and Nonlinear Guidance Law (NGL) [35] are compared in the following part. It may be noted that RTPN and IPN are extensions of TPN and GTPN respectively. It means that they share the same properties, so TPN and GTPN guidance laws can also be represented by RTPN and IPN. Hence, we leave out the TPN and GTPN from our comparison.

The command acceleration by the generalized PN scheme can be expressed by the following vector cross product:

$$\ddot{u}^{des} = n\vec{L} \times \dot{\vec{\theta}} \quad (5.2)$$

where $\vec{\theta}$ is the LOS rate, n is the navigation gain, $\vec{L}$ is the normal to direction of the commanded acceleration, and is calculated differently for different navigation methods using the following equations:

$$\begin{aligned} 1)RTPN : \quad & \vec{L} = \vec{u}_T - \vec{u}_{UAV} \\ 2)IPN : \quad & \vec{L} = \dot{\vec{u}}_T - \dot{\vec{u}}_{UAV} \\ 3)PPN : \quad & \vec{L} = -\dot{\vec{u}}_{UAV} \end{aligned} \quad (5.3)$$

And $\vec{\theta}$ can be expressed as:

$$\vec{\theta} = \frac{(\vec{u}_T - \vec{u}_{UAV}) \times (\dot{\vec{u}}_T - \dot{\vec{u}}_{UAV})}{|\vec{u}_T - \vec{u}_{UAV}|^2} \quad (5.4)$$

NGL can be expressed as:

$$\ddot{u}^{des} = n \cdot \frac{\dot{\vec{u}}_{UAV}}{|\vec{u}_T - \vec{u}_{UAV}|} \cdot \sin\lambda \quad (5.5)$$

λ is the angle between interception velocity and LOS of target.

Figure 5.1: Schematic Show in Different Variables Used in the Guidance Laws

Figure 5.1 shows a pictorial representation of different variables used in the different guidance laws. As mentioned in Chapter 3, when the distance between the UAV and the target becomes small, the PN tracking method generates a very high oscillation such as shown in Figure 5.2. In this figure, we overcome this issue with the use of a switching strategy that allows the PN tracking method to switch to PD tracking method, which has been introduced in Section 5.1, once the UAV comes within a specified distance from the target.

Figure 5.2: Phase Plot Showing a Comparison of PN and PD to Track a Target with Constant Velocity

The results are obtained for tracking a target moving with constant velocity based on RTPN, IPN, PPN and NGL that exploit the switching strategy are compared. Convergence time is used as a parameter to evaluate these methods, which is defined as the time taken for relative distance between UAV and target to converge below 0.5 meters. Before we present our results, it may be noted that to obtain a fair comparison, we assumed an acceleration constraint to represent the maximum achievable acceleration of the UAV. We then tuned the parameters of the above methods so that for the cases considered in this paper, the maximum acceleration provided by the above strategies were constrained by the chosen acceleration constraint value.

Figure 5.3a shows the UAV trajectories for IPN, RTPN, PPN and NGL based methods when tracking a target moving with constant velocity; the UAV starts from (0,0) and target starts from (-5m,5m). The target moves with constant velocity of

0.4m/sec, velocity constraint is 0.5m/sec, UAV initial velocity is 0.6m/sec along the x-direction. Figure 5.3a and Table 5.1 show that IPN and NGL have better results than the others.

Next to test their robustness to variation in initial conditions, we increase the initial relative distance and keep all the parameters unchanged, the results show that RTPN and PPN are no longer able to track the target.

Figure 5.3b shows the UAV trajectories for IPN, RTPN, PPN and NGL based methods when tracking a target moving with constant velocity; the UAV starts from (0,0) and target starts from (-10m,10m). The target moves with constant velocity of 0.2m/sec, velocity constraint is 0.5m/sec, UAV initial velocity is 0.6m/sec along the X-direction. The results shown in Figure 5.3b and in Table 5.2, demonstrate that IPN and NGL based strategies provide tracking results with similar performance. The strategies based on RTPN and PPN, on the other hand, do not lead to a convergent tracking performance.

Similarly, in another simulation study, we reduced the initial velocity of the UAV and found that IPN and NGL based method converged with similar performance, PPN based strategy converged with a worse performance, and RTPN based strategy did not converge at all. The results for this case are shown in Figure 5.3c and Table 5.3. Figure 5.3c shows the UAV trajectories for IPN, RTPN, PPN and NGL based methods when tracking a target moving with constant velocity. The UAV starts from (0,0) and target starts from (-5m,5m). The target moves with constant velocity of 0.2m/sec, velocity constraint is 0.5m/sec, UAV initial velocity is 0.4m/sec along the X-direction.

Figure 5.3: Different Scenarios to Compare IPN, RTPN, NGL and PPN

Methods	IPN	RTPN	PPN	NGL
Time	3.79sec	5.13sec	6.98sec	3.75sec

Table 5.1: Convergence Time for IPN, RTPN, PPN AND NGL in Case 1

Methods	IPN	RTPN	PPN	NGL
Time	5.83sec	N/A	N/A	5.21sec

Table 5.2: Convergence Time for IPN, RTPN, PPN AND NGL in Case 2

The above simulation studies demonstrated that both IPN and NGL based methods were good candidate strategies. We, then, carried out a more detailed numerical

Methods	IPN	RTPN	PPN	NGL
Time	4.6sec	N/A	N/A	4.47sec

Table 5.3: Convergence Time for IPN, RTPN, PPN AND NGL in Case 3

study in which we varied the initial relative distance between the UAV and the target from 5m to 35m, and compared the convergence time for the IPN and NGL based methods. In this study, the target moves with constant velocity of 0.2m/sec, velocity constraint is 0.5m/sec, UAV's initial velocity is 0.4m/sec along the X-direction. The result obtained is plotted in Figure 5.4. It can be seen from the figure, IPN provided more time optimal results. Hence, we picked IPN based method as our strategy for guidance.

Figure 5.4: Plot Comparing the Convergence Time for IPN and IGL

5.3 Simulation Results

Simulation study helps us by allowing us to provide any desired motion to the target and make it more maneuverable, something that can be harder to do in experiments. The switch points are obtained in a trial and error fashion based on a number of

numerical simulations. Before we present our results, it may be noted that to obtain a fair comparison, we assumed an acceleration constraint to represent the maximum achievable acceleration of the UAV. We then tuned the parameters of PD and PN method so that for the cases considered in this paper, the maximum acceleration provided by the PD/PN strategies were constrained by the chosen acceleration constraint value.

Three scenarios are considered in this study:

Case 1: the target moves in a straight line with a constant velocity. To be specific, the UAV starts from (0,0) and target starts from (10m,10m). The target moves with constant velocity of 0.4m/sec. The simulation results are shown in Figure 5.5. Figure 5.5a shows the trajectories of the target and UAV, Figure 5.5b shows the relative distance plotted against time, and Figure 5.5c shows the desired accelerations obtained by PD and PN based strategies.

Case 2: The target moves in a straight line with random velocity. To be specific, the UAV starts from (0,0) and target starts from (10m,10m). The target moves with random velocity between 0 to 1m/sec. The simulation results are shown in Figure 5.6. Figure 5.6a shows the trajectories of the target and UAV, Figure 5.6b shows the relative distance plotted against time, and Figure 5.6c shows the desired accelerations obtained by PD and PN based strategies.

Case 3: The target moves along a sinusoidal curve. To be specific, the UAV starts from (0,0) and target starts from (10m,10m). The target moves with velocity given by $\sin \cdot 0.2t$. UAV initial velocity is 2.2 m/sec. The simulation results are shown in Figure 5.7. Figure 5.7a shows the trajectories of the target and UAV, Figure 5.7b

shows the relative distance plotted against time, and Figure 5.7c shows the desired accelerations obtained by PD and PN based strategies.

From all of cases, we can see that PN based strategy is able to carry out the target tracking even for the high maneuvering target and converges to the target faster than the PD based method.

Figure 5.5: Case 1 Simulation Study.

(a)

(b)

(c)

Figure 5.6: Case 2 Simulation Study.

Figure 5.7: Case 3 Simulation Study.

5.4 Experimental Results

To demonstrate applicability of our PN based switch tracking strategy on quadrotor dynamics and reliability of the simulation results, this strategy has been implemented in several practical scenarios in our experimental environment.

5.4.1 Experimental Facilities

In the experimental part of this thesis, two type of quadrotors are used: Ascending Tech Pelican Quadrotors (Figure 1.1) and Parrot AR. Drone 1.0 Quadrotor (Figure 5.8).

Asctec Pelican is designed for maximum power combined with plenty of room to use its complete capacity built by German company Ascending Tech. It carries a ARM processor and enables a payload up to 1.43 pounds in weight. The light weight, 2.2 pounds, tower structure lets customer easily access its all electronics. Furthermore, it can integrate individual sensors and process the gathered data directly on-board the flight vehicle.

Parrot AR. Drone 1.0 Quadrotor, built by the French company Parrot, is the first quadcopter that can be controlled by a smartphone or tablet. The airframe of the AR Drone, constructed of plastic and carbon fiber part, measures 56 cm in length across. Inside the airframe, a range of sensors assisted flight is available for enabling pilot to operate drone simply and remotely.

Figure 5.8: Parrot AR. Drone 1.0 Quadrotor

K-team Corporation Khepera III ground robot is utilized as a mobile ground target (Figure 5.9). This robot is built by the Swiss company K-Team Corporation. This mini-robot involves a upgradeable embedded computing power, multiple sensor arrays for both long and short range object direction, swappable battery pack system and differential drive odometry.

Figure 5.9: K-team Corporation Khepera III

A 24-camera OptiTrack system is used to provide feedback of position and orientation of the quadrotor and that of the target. This system offers integrated image capture, processing, and motion tracking in a powerful, compact package. It has user-changeable M12 lenses, and Filter Switch Technology.

Screen shot for experimental setup can be seen in Figure 5.10. In this figure, AscTec Pelican and Parrot Drone is tracking Khepera III using positional feedback obtained from OptiTrack System.

(a)

(b)

Figure 5.10: Experimental Screen Shot

5.4.2 Schematic of Experimental Setup

Figure 5.11: Schematic of Experimental Setup

Figure 5.11 shows a schematic diagram of our experimental set-up.

OptiTrack system collects 3-D position and orientation data of the UAV and 2-D positional information of the ground target during each iteration of the algorithm. To make use of the OptiTrack System, a software called OptiTrack Tracking Tool is used. It provides calibration and real-time 3D optical tracking of multiple rigid bodies tracking across multiple OptiTrack cameras. After setting up the physical camera, calibration is necessary to establish connection between each camera. The calibration process can be seen in Figure 5.12. Next, the object files for the UAV and the ground robot need to be established through choosing corresponding markers on each object in the software which provides the object for camera navigation. Figure 5.13

shows the projects of UAV and ground robot. Since the MATLAB interface is built for communication between the devices, a tracking tool Application Programming Interface (API) is used to read data from OptiTrack Tracking Tool to MATLAB.

Figure 5.12: Calibration Process Showing Trajectory of Calibration Wand

Figure 5.13: Project File Establishment

As mentioned before, the MATLAB interface is also built for receiving and transmitting data between PC and UAVs. Different UAVs use different communication protocols, for example, serial port communication for AscTec Pelican and UDP port communication for Parrot Drone. Similarly, data format of low level processors are

different for different quadrotors for example, Hex Values for AscTec Pelican and Binary Values for Parrot Drone. A communication framework has been built to open/close specific port and convert decimal values into specific format in MATLAB and to communicate with the onboard processor of the quadrotors. The target maneuver is controlled by another PC. Linux environment and Player software are used to communicate with the Khepera III robot.

5.4.3 Experimental Results

The experiments using Pelican UAVs were performed for two cases. The results obtained from the experiments are shown in Figure 5.14.

Case (1): The UAV starts from location (0.25, 0.8) and the target starts from location(-0.35, 0.55). The target moves with a constant constant velocity of 0.1m/sec;
Case (2): The UAV starts from location(0.3, 0.8) and the target starts from location(-0.35,0.6). The target moves with constant velocity of 0.15m/sec.

The Figure 5.14a and Figure 5.14c show the 2D views of the target and UAV trajectories for method for case 1 and case 2 respectively. The Figure 5.14b and Figure 5.14d show the positional error between the UAV and the target during the tracking process for case 1 and case 2 respectively. The trajectories for the UAV and the target are shown for case 1 in Figure 5.15.

(a)

(b)

(c)

(d)

Figure 5.14: Experimental Results for 2 Cases with Pelican UAV.

Figure 5.15: The UAV and the Target Trajectory in 3D for Case 1

The experiments using Parrot Drone UAVs were performed using two cases. The results obtained from the experiments are shown in Figure 5.16.

Case (1): The UAV starts from location (0.1, 0) and the target starts from location(1.1, 0.6). The target moves with a constant constant velocity of 0.1m/sec;
Case (2): The UAV starts from location(-0.1, -0.1) and the target starts from location(1.2,1.3). The target moves with a fast changing maneuver.

The figure 5.16a and 5.16c show the 2D vews of the target and UAV trajectories for each method for case 1 and case 2 respectively. The figure 5.16b and 5.16d show the positional error between the UAV and the target during the tracking process in case 1 and case 2.

(a)

(b)

(c)

(d)

Figure 5.16: Experimental Results for 2 Cases with Parrot Drone UAV.

Chapter 6

Optimal Switching Strategy for Non-maneuvering target

In this chapter, optimal switching strategy is proposed to solve Problem 2 in Chapter 3 for non-maneuvering target. Considering different forms of PN method for non-maneuvering and maneuvering target, our strategy consists of two approaches for different target's maneuvers. This chapter presents the approach for non-maneuvering target. Here, a non-maneuvering target is defined to have a constant velocity during its entire motion. Analytical solutions of the PN and PD methods are introduced and used in this strategy. The accuracy and reliability of this strategy are validated by the simulation results.

6.1 Theoretical Analysis

First, the PD tracking method is analyzed. It may be noted that the PD tracking method forms the second part of the proposed strategy. PD tracking method can be written as:

$$\ddot{r}_i + K_d \dot{r}_i + K_p r_i = 0 \quad (6.1)$$

where r_i is the relative distance (position error) between UAV and target in i dimension, K_p and K_d are the PD control gains. As in [41], Equation 6.1 presents a well known second-order differential equation with constant coefficients. The Laplace transform for 6.1 is given as:

$$s^2 + K_d s + K_p = 0 \quad (6.2)$$

Here, for the sake of simplicity, we consider that the system is critically damped. Hence, we have:

$$K_d = 2\sqrt{K_p} \quad (6.3)$$

Therefore, our choice of PD control gains should always satisfy Equation 6.3. By solving Equation 6.1, while using Equation 6.3, one obtains:

$$r_i(t) = \left\{ r_i(0) + \left[\dot{r}_i(0) + \frac{K_d}{2} r_i(0) \right] t \right\} e^{\frac{-K_d t_{PD}}{2}} \quad (6.4)$$

where $r_i(0), \dot{r}_i(0)$ denote the initial errors in position and velocity between UAV and target, t denotes operating time of PN tracking method. It may be noted that initial conditions for the PD tracking method are derived from the UAV states at the end of PN tracking method or at $t = t_{PN}$. So Equation 6.4 can be written as :

$$\begin{aligned} r_i(t_f) &= \left\{ r_i(t_{PN}) + \left[\dot{r}_i(t_{PN}) + \frac{K_d}{2} r_i(t_{PN}) \right] t_{PD} \right\} e^{\frac{-K_d t_{PD}}{2}} \\ &= \left\{ \left(1 + \frac{K_d}{2} t_{PN} \right) r_i(t_{PD}) + t_f \dot{r}_i(t_{PN}) \right\} e^{\frac{-K_d t_{PD}}{2}} \end{aligned} \quad (6.5)$$

t_{PD}, t_{PN} denote operation time for PD and PN respectively. Considering our tracking problem in 2-dimension, the total position error r at time $t_f = t_{PN} + t_{PD}$ can be written as:

$$r^2(t_f) = r_x^2(t_f) + r_y^2(t_f) \quad (6.6)$$

To solve Equation 6.6, the relationship between r_i and t_{PN} should be solved, which means that it is necessary to obtain analytical solution of PN tracking method. The relative velocity between interceptor and its target expressed in polar coordinates as can be written as [27]:

$$v = \dot{r} \vec{e}_r + r \dot{\theta} \vec{e}_\theta \quad (6.7)$$

Figure 6.1: Planar Tracking Geometry

As shown in Figure 6.1, v is the relative velocity between the UAV and the target expressed in polar coordinates, r is the distance of LOS, θ is LOS angle, $\vec{e}_r$ is unit vector along with LOS, $\vec{e}_\theta$ is unit vector along the normal direction of LOS. Thus we can obtain relative acceleration by taking a derivative of Equation 6.7 using $\dot{\vec{e}}_\theta = -\dot{\theta}\vec{e}_r$:

$$\begin{aligned}
 a &= \ddot{r}\vec{e}_r + \dot{r}\dot{\theta}\vec{e}_\theta + \dot{r}\dot{\theta}\vec{e}_\theta + r\ddot{\theta}\vec{e}_\theta - r\dot{\theta}^2\vec{e}_r \\
 &= \left(\ddot{r} - r\dot{\theta}^2\right)\vec{e}_r + \left(r\ddot{\theta} + 2\dot{r}\dot{\theta}\right)\vec{e}_\theta
 \end{aligned} \tag{6.8}$$

Also, relative acceleration can be obtained from Equation 5.3 by:

$$\begin{aligned}
a &= a_{UAV} - a_T \\
&= \lambda \dot{\theta} \vec{e}_z \times \dot{r} - 0 \\
&= \lambda \left(-r \dot{\theta}^2 \vec{e}_r + \dot{r} \dot{\theta} \vec{e}_\theta \right)
\end{aligned} \tag{6.9}$$

where $\vec{e}_z = \vec{e}_r \times \vec{e}_\theta$, λ is the control gain, a_{UAV}, a_T are the real-time acceleration of the UAV and the target. From Equation 6.8 and Equation 6.9, we obtain:

$$\begin{aligned}
-\lambda r \dot{\theta}^2 &= \ddot{r} - r \dot{\theta}^2 \\
\lambda \dot{r} \dot{\theta} &= r \ddot{\theta} + 2\dot{r} \dot{\theta}
\end{aligned} \tag{6.10}$$

From Equation 6.10, we can obtain $\dot{\theta}$ as:

$$\dot{\theta} = \dot{\theta}_0 \left(\frac{r}{r_0} \right)^{\lambda-2} \tag{6.11}$$

where θ_0, r_0 are initial LOS angle and relative velocity. By substituting Equation 6.11 into Equation 6.10, the solution of $\dot{r}$ can be obtained as

$$\dot{r}^2 = v_0^2 - r_0^2 \dot{\theta}_0^2 (r/r_0)^{2\lambda-2} \tag{6.12}$$

Thus t_{PN} can be solved as a function of r :

$$t_{PN} = \int_{r_0}^r \frac{dr}{\dot{r}} = - \int_{r_0}^r \frac{dr}{\sqrt{v_0^2 - r_0^2 \dot{\theta}_0^2 (r/r_0)^{2\lambda-2}}} \quad \text{where} \quad \dot{r}_0 \leq 0 \quad (6.13)$$

In this thesis, we consider two cases that $\lambda = 2$ and $\lambda = 1$. When $\lambda = 2$, Equation 6.13 become:

$$\begin{aligned} t_{PN} &= - \int_{r_0}^r \frac{dr}{\sqrt{v_0^2 - r_0^2 \dot{\theta}_0^2 (r/r_0)^2}} \\ \Rightarrow t_{PN} &= - \frac{1}{\dot{\theta}_0} \int_{r_0}^r \frac{dr}{\sqrt{a^2 - r^2}} \quad a = \frac{v_0}{\dot{\theta}_0} \\ \Rightarrow t_{PN} &= - \frac{1}{\dot{\theta}_0} \left(\arcsin \frac{r}{a} - \arcsin \frac{r_0}{a} \right) \\ \Rightarrow \frac{r}{a} &= \sin \left(\arcsin \frac{r_0}{a} - \dot{\theta}_0 t_{PN} \right) \\ \Rightarrow r &= a \sin \left(b - \dot{\theta}_0 t_{PN} \right) \quad b = \arcsin \frac{r_0}{a} \end{aligned} \quad (6.14)$$

To project total position error onto the X-Y plane, the LOS angle can be obtained from Equation 6.11 and substituting $\lambda = 2$:

$$\Rightarrow \dot{\theta} = \dot{\theta}_0 \Rightarrow \theta = \dot{\theta}_0 t_{PN} + \theta_0 \quad (6.15)$$

From Equation 6.14 and Equation 6.15, we can obtain r_x, r_y as:

$$\begin{aligned} r_x &= r \cos \theta = a \sin \left(b - \dot{\theta}_0 t_{PN} \right) \cos \left(\dot{\theta}_0 t_{PN} + \theta_0 \right) \\ r_y &= r \sin \theta = a \sin \left(b - \dot{\theta}_0 t_{PN} \right) \sin \left(\dot{\theta}_0 t_{PN} + \theta_0 \right) \end{aligned} \quad (6.16)$$

$\dot{r}_x, \dot{r}_y$ can be obtained from taking derivatives of the above equation:

$$\begin{aligned}\dot{r}_x &= -\dot{\theta}_0 (a) \cos \left(-2\dot{\theta}_0 t_{PN} + b - \theta_0 \right) \\ \dot{r}_y &= -\dot{\theta}_0 (a) \sin \left(2\dot{\theta}_0 t_{PN} - b + \theta_0 \right)\end{aligned}\tag{6.17}$$

We put the variables in Equation 6.16 and Equation 6.17 into Equation 6.5 and then use MATLAB's function `fminbnd` in Equation 6.6 for the calculation of the optimal switching time t_{PN} .

When $\lambda = 1$, Equation 6.13 becomes:

$$\begin{aligned}t_{PN} &= - \int_{r_0}^r \frac{dr}{\sqrt{v_0^2 - r_0^2 \dot{\theta}_0^2}} \\ \Rightarrow t_{PN} &= \frac{-1}{\sqrt{v_0^2 - r_0^2 \dot{\theta}_0^2}} (r - r_0) \\ \Rightarrow r &= r_0 - t_{PN} \sqrt{v_0^2 - r_0^2 \dot{\theta}_0^2}\end{aligned}\tag{6.18}$$

To project total position error onto the X-Y plane, the LOS angle can be obtained from 6.11 and substituting $\lambda = 1$:

$$\dot{\theta} = \dot{\theta}_0(r_0/r)$$

put variables in Equation 6.18 in

$$\begin{aligned}\dot{\theta} &= \dot{\theta}_0 \frac{r_0}{r_0 - t_{PN} \sqrt{v_0^2 - r_0^2 \dot{\theta}_0^2}} \\ \text{denote } c &= \sqrt{v_0^2 - r_0^2 \dot{\theta}_0^2} \\ \dot{\theta} &= \dot{\theta}_0 \frac{r_0}{r_0 - t_{PNC}} \\ \theta &= \dot{\theta}_0 \int_0^{t_{PN}} \frac{r_0}{r_0 - t_{PNC}} dt_{PN} \\ \theta &= \dot{\theta}_0 r_0 \left(-\frac{1}{c} \ln \left| 1 - \frac{t_{PNC}}{r_0} \right| \right) \\ \theta &= -\frac{\dot{\theta}_0 r_0}{c} \ln \left(1 - \frac{t_{PNC}}{r_0} \right)\end{aligned}\tag{6.19}$$

From Equation 6.18 and 6.19, we can obtain r_x, r_y from:

$$\begin{aligned}r_x &= r \cos \theta = (r_0 - t_{PNC}) \cos \left(-\frac{\dot{\theta}_0 r_0}{c} \ln \left(1 - \frac{t_{PNC}}{r_0} \right) \right) \\ r_y &= r \sin \theta = (r_0 - t_{PNC}) \sin \left(-\frac{\dot{\theta}_0 r_0}{c} \ln \left(1 - \frac{t_{PNC}}{r_0} \right) \right)\end{aligned}\tag{6.20}$$

$\dot{r}_x, \dot{r}_y$ can be obtained from taking derivatives of the above equations:

$$\begin{aligned}
\dot{r}_x &= -c \times \cos \left(-\frac{\dot{\theta}_0 r_0}{c} \ln \left(1 - \frac{t_{PNC}}{r_0} \right) \right) - \\
&\quad \dot{\theta}_0 r_0 \times \sin \left(-\frac{\dot{\theta}_0 r_0}{c} \ln \left(1 - \frac{t_{PNC}}{r_0} \right) \right) \\
\dot{r}_y &= -c \times \sin \left(-\frac{\dot{\theta}_0 r_0}{c} \ln \left(1 - \frac{t_{PNC}}{r_0} \right) \right) + \\
&\quad \dot{\theta}_0 r_0 \times \cos \left(-\frac{\dot{\theta}_0 r_0}{c} \ln \left(1 - \frac{t_{PNC}}{r_0} \right) \right)
\end{aligned} \tag{6.21}$$

As same as the previous case $\lambda = 2$, we put variables in Equation 6.20 and Equation 6.21 into Equation 6.5, then use MATLAB function `fminbnd` to Equation 6.6 for calculation of optimal switching time t_{PN} .

6.2 Simulation Results

Simulation study helps us demonstrate the robustness to different initial condition of the UAV and the target and accuracy of our optimal switching strategy. To make sure the comparison is fair, k_p parameters are modified to make the maximum value of the desired acceleration of PN/PD tracking methods be constrained to certain value. Several scenarios are considered in this study:

$$(1) \lambda = 2$$

A number of simulation studies are carried out using a number of cases where initial relative positions and velocities are varied. Four cases are considered:

Case 1: The UAV starts from (0,0) and the target starts from (50m, 20m). The

target moves with initial velocity of 0.4 m/sec in X direction only, UAV initial velocity is 5.6 m/sec in X direction only. Figure 6.2a is the relative distance plotted against time when using different switching points; Figure 6.2b is the desired acceleration obtained by using different switching points. Observation time t_f is set to 25 sec.

Case 2: The UAV starts from (0,0) and the target starts from (50m, 20m). The target moves with initial velocity of 5 m/sec in X direction; initial velocity of 3 m/sec in Y direction, UAV initial velocity is 3.57 m/sec in X direction and 2.14 m/sec in Y direction. Figure 6.3a is the relative distance plotted against time when using different switching points; Figure 6.3b is the desired acceleration obtained by using different switching points. Observation time t_f is set to 50 sec.

Case 3: The UAV starts from (0,0) and the target starts from (150m, 200m). The target moves with initial velocity of 2 m/sec in X direction; initial velocity of 1 m/sec in Y direction, UAV initial velocity is 5.15 m/sec in X direction and 2.57 m/sec in Y direction. Figure 6.4a is relative distance plotted against time when using different switching points; Figure 6.4b is desired acceleration obtained by using different switching points. Observation time t_f is set to 60 sec.

Case 4: The UAV starts from (0,0) and the target starts from (150m, 200m). The target moves with initial velocity of 2 m/sec in X direction; initial velocity of 1 m/sec in Y direction, UAV initial velocity is 6.94 m/sec in X direction and 3.47 m/sec in Y direction. Figure 6.5a is the relative distance plotted against time when using different switching points; Figure 6.5b is the desired acceleration obtained by using different switching points. Observation time t_f is set to 40 sec.

(a)

(b)

Figure 6.2: Simulation Results for Case 1 ($\lambda = 2$)

(a)

(b)

Figure 6.3: Simulation Results for Case 2 ($\lambda = 2$)

Figure 6.4: Simulation Results for Case 3 ($\lambda = 2$)

Figure 6.5: Simulation Results for Case 4 ($\lambda = 2$)

$$(2)\lambda = 1$$

A number of simulation studies are carried out using a number of cases where initial relative positions and velocities are varied. Four cases are considered:

Case 1: The UAV starts from (0,0) and the target starts from (50m, 20m). The target moves with initial velocity of 0.4 m/sec in X direction only, UAV initial velocity

is 5.6 m/sec in X direction only. Figure 6.6a is the relative distance plotted against time when using different switching points; Figure 6.6b is the desired acceleration obtained by using different switching points. Observation time t_f is set to 25 sec.

Case 2: The UAV starts from (0,0) and the target starts from (50m, 20m). The target moves with initial velocity of 5 m/sec in X direction; initial velocity of 3 m/sec in Y direction, UAV initial velocity is 3.57 m/sec in X direction and 2.14 m/sec in Y direction. Figure 6.7a is the relative distance plotted against time when using different switching points; Figure 6.7b is the desired acceleration obtained by using different switching points. Observation time t_f is set to 15 sec.

Case 3: The UAV starts from (0,0) and the target starts from (150m, 200m). The target moves with initial velocity of 2 m/sec in X direction; initial velocity of 1 m/sec in Y direction, UAV initial velocity is 5.15m/sec in X direction and 2.57m/sec in Y direction. Figure 6.8a is the relative distance plotted against time when using different switching points; Figure 6.8b is the desired acceleration obtained by using different switching points. Observation time t_f is set to 40 sec.

Case 4: The UAV starts from (0,0) and the target starts from (150m, 200m). The target moves with initial velocity of 2 m/sec in X direction; initial velocity of 1 m/sec in Y direction, UAV initial velocity is 6.94 m/sec in X direction and 3.47 m/sec in Y direction. Figure 6.9a is the relative distance plotted against time when using different switching points; Figure 6.9b is the desired acceleration obtained by using different switching points. Observation time t_f is set to 40 sec.

(a)

(b)

Figure 6.6: Simulation Results for Case 1 ($\lambda = 1$)

(a)

(b)

Figure 6.7: Simulation Results for Case 2 ($\lambda = 1$)

Figure 6.8: Simulation Results for Case 3 ($\lambda = 1$)

Figure 6.9: Simulation Results for Case 4 ($\lambda = 1$)

From the above simulation studies, we can conclude that the proposed optimal switching strategy always obtain the optimal results for both cases when $\lambda = 2$ and $\lambda = 1$.

Chapter 7

Optimal Switching Strategy for Maneuvering Target

In this chapter, optimal switching strategy is proposed to solve Problem 2 in Chapter 3 for maneuvering target. An augmented ideal proportional navigation methods has been used for tracking maneuvering target and an optimal switch strategy has been proposed. The accuracy and reliability of this strategy are validated by simulation results.

7.1 Theoretical Analysis

For maneuvering targets, PD tracking method is as same as for non-maneuvering target. So, we only carry out an analytical solution for the proposed PN tracking method here. Based on [27], relative acceleration can be obtained by taking derivative

Equation 6.7 :

$$\begin{aligned}
a &= \ddot{r}\vec{e}_r + \dot{r}\dot{\theta}\vec{e}_\theta + \dot{r}\ddot{\theta}\vec{e}_\theta + r\ddot{\theta}\vec{e}_\theta - r\dot{\theta}^2\vec{e}_r \\
&= \left(\ddot{r} - r\dot{\theta}^2\right)\vec{e}_r + \left(r\ddot{\theta} + 2\dot{r}\dot{\theta}\right)\vec{e}_\theta
\end{aligned} \tag{7.1}$$

From PN tracking method, relative acceleration also can be obtained as:

$$\begin{aligned}
a &= a_{UAV} - a_T \\
&= \lambda\dot{\theta}\vec{e}_z \times v - a_T\vec{e}_z \times \vec{e}_v \\
&= \left(-\lambda r\dot{\theta}^2 + \frac{a_T}{v}r\dot{\theta}\right)\vec{e}_r + \left(\lambda\dot{r}\dot{\theta} - \frac{a_T}{v}\dot{r}\right)\vec{e}_\theta
\end{aligned} \tag{7.2}$$

From Equation 7.1 and 7.2, we obtain:

$$\begin{aligned}
-\lambda r\dot{\theta}^2 + \frac{a_T}{v}r\dot{\theta} &= \ddot{r} - r\dot{\theta}^2 \\
\lambda\dot{r}\dot{\theta} - \frac{a_T}{v}\dot{r} &= r\ddot{\theta} + 2\dot{r}\dot{\theta}
\end{aligned} \tag{7.3}$$

Though [27] provides an analytical solution for Equation 7.3, constraint needs to be put on maneuver of target acceleration. For simplicity, we assume $a_T = -b\dot{r}$. Thus this tracking method may not be applicable when target performs fast maneuver such as evasive maneuver. In addition, the solution of 7.3 is inherently complex to obtain the relationship between r and t_{PN} [27].

To overcome these problems, general ideal proportional navigation has been replaced by an augmented ideal proportional navigation law in this thesis. Augmented ideal proportional navigation has been widely applied in research [29]. Thus aug-

mented PN tracking method, the acceleration of the UAV is given by:

$$a_{UAV} = \lambda \dot{\theta} \vec{e}_z \times v + a_T \quad (7.4)$$

From Equation 7.4, relative acceleration can be obtained from:

$$\begin{aligned} a &= a_{UAV} - a_T \\ &= \lambda \dot{\theta} \vec{e}_z \times v + a_T - a_T \\ &= \lambda \left(-r \dot{\theta}^2 \vec{e}_r + \dot{r} \dot{\theta} \vec{e}_\theta \right) \end{aligned} \quad (7.5)$$

From Equation 7.1 and Equation 7.5, we obtain:

$$\begin{aligned} -\lambda r \dot{\theta}^2 &= \ddot{r} - r \dot{\theta}^2 \\ \lambda \dot{r} \dot{\theta} &= r \ddot{\theta} + 2\dot{r} \dot{\theta} \end{aligned} \quad (7.6)$$

It is obvious that Equation 7.6 is same as Equation 6.10. Thus optimal switching time t_{PN} can be derived in the similar manner Equation 6.14- Equation 6.17, when $\lambda = 2$ and from Equation 6.18 - Equation 6.21, when $\lambda = 1$.

7.2 Simulation Results

Simulation study helps us demonstrate the robustness to the different initial conditions between the UAV and the target and accuracy of our optimal switching strategy. To make sure the comparison is fair, k_p parameters are modified to make the max-

imum value of desired acceleration of PN/PD tracking methods be constrained to certain value. Several scenarios are considered in this study:

$$(1)\lambda = 2$$

A number of simulation studies are carried out using a number of cases where initial relative positions and velocities are varied. Three cases are considered:

Case 1: The UAV starts from (0,0) and the target starts from (150m, 100m). The target moves with initial velocity of 0.4 m/sec in X direction and constant acceleration 0.1 m/sec²; initial velocity of 0.2 m/sec in Y direction and constant acceleration 0.1 m/sec², UAV initial velocity is 8.54 m/sec in X direction and 4.27 m/sec in Y direction. Figure 7.1a is the relative distance plotted against time when using different switching points; Figure 7.1b is the desired acceleration obtained by using different switching points. Observation time t_f is set to 25 sec.

Case 2: The UAV starts from (0,0) and the target starts from (150m, 100m). The target moves with initial velocity of 2 m/sec in X direction and constant acceleration 1 m/sec²; initial velocity of 1 m/sec in Y direction and constant acceleration 0.8 m/sec², UAV initial velocity is 6.94 m/sec in X direction and 3.47 m/sec in Y direction. Figure 7.2a is the relative distance plotted against time when using different switching points; Figure 7.2b is the desired acceleration obtained by using different switching points. Observation time t_f is set to 35 sec.

Case 3: The UAV starts from (0,0) and the target starts from (150m, 100m). The target moves with initial velocity of 0.4 m/sec in X direction and acceleration which increases 0.005 m/sec² each second; initial velocity of 0.2m/sec in Y direction

and acceleration which increases 0.005 m/sec^2 each second, UAV initial velocity is 8.54 m/sec in X direction and 4.27 m/sec in Y direction. Figure 7.3a is the relative distance plotted against time when using different switching points; Figure 7.3b is the desired acceleration obtained by using different switching points. Observation time t_f is set to 40 sec.

Figure 7.1: Simulation Results for Case 1 ($\lambda = 2$).

Figure 7.2: Simulation Results for Case 2 ($\lambda = 2$).

Figure 7.3: Simulation Results for Case 3 ($\lambda = 2$).

From above cases, we can find that the proposed optimal switching strategy always provides the most optimal result.

$$(2)\lambda = 1$$

A number of simulation studies are carried out using a number of cases where initial relative positions and velocities are varied. Three cases are considered:

Case 1: The UAV starts from (0,0) and the target starts from (150m, 100m). The target moves with initial velocity of 0.4 m/sec in X direction and constant acceleration 0.1 m/sec²; initial velocity of 0.2 m/sec in Y direction and constant acceleration 0.1 m/sec², UAV initial velocity is 8.54 m/sec in X direction and 4.27 m/sec in Y direction. Figure 7.4a is the relative distance plotted against time when using different switching points; Figure 7.4b is the desired acceleration obtained by using different switching points. Observation time t_f is set to 25 sec.

Case 2: The UAV starts from (0,0) and the target starts from (150m, 100m). The

target moves with initial velocity of 2 m/sec in X direction and constant acceleration 1 m/ sec^2 ; initial velocity of 1 m/sec in Y direction and constant acceleration 0.8 m/ sec^2 , UAV initial velocity is 6.94 m/sec in X direction and 3.47 m/sec in Y direction. Figure 7.5a is the relative distance plotted against time when using different switching points; Figure 7.5b is the desired acceleration obtained by using different switching points. Observation time t_f is set to 35 sec.

Case 3: The UAV starts from (0,0) and the target starts from (150m, 100m). The target moves with initial velocity of 0.4 m/sec in X direction and acceleration which increases 0.005 m/ sec^2 each second; initial velocity of 0.2m/sec in Y direction and acceleration which increases 0.005 m/ sec^2 each second, UAV initial velocity is 8.54 m/sec in X direction and 4.27 m/sec in Y direction. Figure 7.6a is the relative distance plotted against time when using different switching points; Figure 7.6b is the desired acceleration obtained by using different switching points. Observation time t_f is set to 40 sec.

Figure 7.4: Simulation Results for Case 1 ($\lambda = 1$).

(a)

(b)

Figure 7.5: Simulation Results for Case 2 ($\lambda = 1$).

(a)

(b)

Figure 7.6: Simulation Results for Case 3 ($\lambda = 1$).

From above cases, we can find that the proposed optimal switching strategy will always provides the most optimal result.

Chapter 8

Conclusions and Scope for Future Work

8.1 Conclusions

Two main problems have been studied in this thesis. The first problem is developing a target tracking control method for a quadrotor UAV. Another is providing an optimal switching time for the proposed switched tracking strategy.

The definition and motivation of the first problem has been introduced in this thesis as well as the existing tracking methods which are used in quadrotor UAV control. This problem is proposed to be solved by using a guidance and control architecture for UAVs. The architecture has four layers: Trajectory Generation, Trajectory Tracking, Position Control and Motor Control. The quadrotor dynamics and motor

dynamics have been used to handle the problem in the last three layers. As for Trajectory Generation layer, a proportional navigation (PN) based method is developed for quadrotors to track a moving ground target. To overcome the limitation of the PN tracking method for target tracking problem, a PN switched tracking strategy has been proposed. A numerical comparison among existing proportional navigation methods has been made. Based on the comparative study, the Ideal Proportional Navigation has been chosen to be implemented in the proposed switching strategy. The experimental testbed based on both Parrot Drone quadrotor and AscTec Pelican quadrotor is designed to validate the theoretical results. The facilities and their setup have been introduced. The simulation studies show that the proposed tracking method not only achieves an efficient tracking (i.e., smaller positional error) but also gets smaller oscillation when compared to a widely used Proportional Derivative (PD) tracking method even for highly maneuvering target.

The second problem is solving the optimal switching problem, which results from the proposed switched tracking strategy. It is related to finding out when should the switching take place. To solve this problem, PN and PD method are analyzed theoretically for tracking non-maneuvering and maneuvering targets. Augmented Proportional Navigation tracking methods is used for the UAV to track maneuvering targets. As a result, an optimal switching technique is proposed to obtain an optimal switching point for the proposed tracking method. The simulation results show that it is effective and robust to different UAV's initial conditions and target's maneuvers for tracking of both non-maneuvering and maneuvering targets.

8.2 Contributions

The main contributions of this thesis are described as below:

- (i) Existing PN methods are compared and Ideal Proportional Navigation is determined to be more suitable for quadrotor dynamics than others.
- (ii) A PN based switched tracking method is proposed and is able to generate time-efficient tracking trajectory and less oscillation than PD tracking method for target tracking problem (Problem 1).
- (iii) An optimal switching strategy is developed for Optimal Switching Time Problem (Problem 2). The simulation results show that the proposed switching strategy always provide optimal switching point even for fast-maneuvering targets.
- (iv) Proposed switched tracking method is applied to real quadrotors in the experiment.

8.3 Scope for Future Work

There are several future directions for future research as described below:

- (i) The proposed tracking method should be considered for target tracking in different urban terrains. In the simple terrain environment, tracking problem can be defined in a 2D plane. However, in some special terrain like mountainous area, the relative altitude value between the UAV and the target can not be ignored because the relative distance is no longer based on planar motion of target. Thus in this

case, the proposed tracking method needs to be extended to 3D. On the other hand, the obstacle avoidance mechanism should be added to the proposed tracking method since the obstacles could appear on the trajectory.

(ii) The real-time tracking data could be combined with noise which is generated due to the limitation of camera or the process of transmitting camera data. Thus the sensitivity for noise of the proposed optimal switching strategy should be tested by adding noise on the feedback data of states of the UAV and the target in simulation. It will help to validate the robustness of the proposed strategy to address noise resulting from sensing and communication. On the other hand, the robustness of the proposed optimal switching strategy should be tested in the experimental platform, considering that the difference of dynamic behavior between real quadrotor model and simulation model may result in different solutions from the proposed optimal switching strategy. In addition, different values for same parameters between experiment and simulation, such as K_p , K_d parameters in PD law for position control of quadrotor, will also lead to different optimal switching point for the same scenario. A system identification method may need to be developed to address these issues.

(iii) In this thesis, the maneuvers of the targets in simulation or experiments are limited. In practice, a target is expected to perform evasive maneuvers. It is necessary to develop evasive maneuvers for the target and test the proposed optimal switching strategy for such targets. Meanwhile, a computer vision based method can be developed to estimate the states for fast maneuvering targets. With these estimations, tracking efficiency of the proposed tracking methods can be improved.

(iv) Though the proposed tracking law is valid in generating a time efficient tra-

jectory, it cannot guarantee a time optimal trajectory. To solve this kind of problem, more research should be done using optimal control theory to generate a time optimal trajectory.

Bibliography

- [1] K. Ladd, R. T. I. International, and S. C. Kaydos-daniels, “Unmanned Aircraft and the Human Element : Public Perceptions and First Responder Concerns,” vol. 2015, no. 112, pp. 1–10, 2013.
- [2] G. Hoffmann, H. Huang, S. Waslander, and C. Tomlin, “Quadrotor Helicopter Flight Dynamics and Control: Theory and Experiment,” *AIAA Guidance, Navigation and Control Conference and Exhibit*, pp. 1–20, Aug. 2007.
- [3] A. Yilmaz, O. Javed, and M. Shah, “Object tracking,” *ACM Computing Surveys*, vol. 38, no. 4, Dec. 2006.
- [4] E. Altug, J. Ostrowski, and C. Taylor, “Quadrotor Control Using Dual Camera Visual Feedback,” in *2003 IEEE International Conference on Robotics and Automation*, vol. 3, 2003, pp. 4294–4299.
- [5] P. Castillo, A. Dzul, and R. Lozano, “Real-time Stablization and Tracking of a Four-motor Mini Rotorcraft,” *IEEE Transaction on Control Systems Technology*, vol. 12, no. 4, pp. 510–516, 2004.

- [6] B. Y. N. Michael, D. Mellinger, Q. Lindsey, and V. Kumar, "The GRASP Multiple Micro-UAV Test Bed," *IEEE Robotics & Automation Magazine*, vol. 17, no. 3, pp. 56–65, 2010.
- [7] N. Guenard, T. Hamel, V. Moreau, and S. A. France, "Dynamic Modeling and Intuitive Control Strategy for an X4-flyer," in *ICCA'05 International Conference on Control and Automation*, 2005, pp. 1–6.
- [8] J. Escareno, S. Salazar-Cruz, and R. Lozano, "Embedded Control of a Four-rotor UAV," in *2006 American Control Conference*. Ieee, 2006.
- [9] E. Nice, "Design of a Four Rotor Hovering Vehicle," Ph.D. dissertation, Cornell University, 2004.
- [10] F.-w. Uavs, R. Beard, D. Kingston, M. Quigley, D. Snyder, R. Christiansen, W. Johnson, T. McLain, and M. A. Goodrich, "Autonomous Vehicle Technologies for Small Fixed Wing UAVs," *AIAA Journal of Aerospace Computing, Information and Communication*, vol. 2, no. January, pp. 92–108, 2005.
- [11] R. W. Beard, "A Class of Flight Trajectories for Tracking Ground Targets with Micro Air Vehicles," *2007 Mediterranean Conference on Control & Automation*, pp. 1–6, Jun. 2007.
- [12] E. N. Johnson and S. K. Kannan, "Adaptive Flight Control for an Autonomous Unmanned Helicopter," in *2002 AIAA Guidance, Navigation and Control Conference*, no. August, 2002.

- [13] L. Doitsidis and K. P. Valavanis, “A Framework for Fuzzy Logic Based UAV Navigation and Control,” in *2004 IEEE International Conference on Robotics and Automation*, no. April, 2004, pp. 4041–4046.
- [14] W. Ren and R. Beard, “CLF-based Tracking Control for UAV Kinematic Models with Saturation Constraints,” *42nd IEEE International Conference on Decision and Control*, vol. 4, pp. 3924–3929, 2003.
- [15] C. Sconyers, I. A. Raptis, and G. J. Vachtsevanos, “Rotorcraft Control and Trajectory Generation for Target Tracking,” *19th Mediterranean Conference on Control and Automation*, pp. 1235–1240, 2011.
- [16] P. Zarchan, *Tactical And Strategic Missile Guidance (2nd ed)*, volume 157 ed., AIAA Inc., Ed. The American Institute of Aeronautics and Astronautics, Inc., 1994.
- [17] G. Hoffmann, S. Waslander, and C. Tomlin, “Quadrotor Helicopter Trajectory Tracking Control,” *AIAA Guidance, Navigation and Control Conference and Exhibit*, pp. 1–14, Aug. 2008.
- [18] N. Regina and M. Zanzi, “2D Tracking and Over-flight of a Target by Means of a Non-linear Guidance Law for UAV,” *2009 IEEE Aerospace conference*, pp. 1–11, Mar. 2009.
- [19] Y. Morel and A. Leonessa, “Direct Adaptive Tracking Control of Quadrotor Aerial Vehicles,” *Dynamic Systems and Control, Parts A and B*, vol. 2006, pp. 155–161, 2006.

- [20] P. Theodorakopoulos and S. Lacroix, "A Strategy for Tracking a Ground Target with a UAV," *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1254–1259, Sep. 2008.
- [21] S. Park, J. Deyst, and J. How, "A New Nonlinear Guidance Logic for Trajectory Tracking," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, pp. 1–16, Aug. 2004.
- [22] P. a. Johnson and R. T. O'Brien, "An Investigation of Interceptor Guidance Methods through Modeling and Simulation," *2007 Thirty-Ninth Southeastern Symposium on System Theory*, pp. 258–262, Mar. 2007.
- [23] M. Mehrandezh, N. M. Sela, R. G. Fenton, and B. Benhabib, "Robotic Interception of Moving Objects Using an Technique," *IEEE Transaction on Systems, Man and Cybernetics*, vol. 30, no. 3, pp. 238–250, 2000.
- [24] M. Guelman, "The Closed-form Solution of True Proportional Navigation," *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-12, no. 4, pp. 472–482, Jul. 1976.
- [25] C. D. Yang, F. B. Yeh, and C. H. Chen, "The Closed-form Solution of Generalized Proportional Navigation," *Journal of Guidance, Control, and Dynamics*, vol. 10, no. 2, pp. 216–218, 1987.
- [26] K. Becker, "Closed-Form Solution of Pure Proportion Navigation," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 26, no. 3, pp. 526–533, 1990.
- [27] P.-J. Yuan and J.-S. Chern, "Ideal Proportional Navigation," *Journal of Guidance, Control, and Dynamics*, vol. 15, no. 5, pp. 1161–1165, Sep. 1992.

- [28] P. R. Mahapatra and U. S. Shukla, "Accurate Solution of Proportional Navigation for Maneuvering Targets," *IEEE Transactions on Aerospace and Electronic Systems*, no. 25, pp. 81–89, 1989.
- [29] C.-d. Yang and C.-c. Yang, "A Unified Approach to Proportional Navigation," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 33, no. 2, pp. 557–567, Apr. 1997.
- [30] P.-J. Yuan and J.-S. Chern, "Solution of True Proportional Navigation for Maneuvering and Nonmaneuvering Targets," *Journal of Guidance, Control, and Dynamics*, vol. 15, no. 1, pp. 268–271, 1990.
- [31] P.-j. Yuan and S.-c. Hsut, "Exact Closed-Form Solution of Generalized Proportional Navigation," *Journal of Guidance, Control, and Dynamics*, vol. 16, no. 5, pp. 963–966, 1993.
- [32] D. Ghose, "On the Generalization of True Proportional Navigation," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 30, no. 2, 1994.
- [33] A. Dhar and D. Ghose, "Capture Region for a Realistic TPN Guidance Law," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 29, no. 3, pp. 995–1003, 1993.
- [34] M. Guelman, "Proportional Navigation with a Maneuvering Target," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 8, no. 3, pp. 364–371, 1972.

- [35] S. Park, J. Deyst, and J. How, “A New Nonlinear Guidance Logic for Trajectory Tracking,” *AIAA Guidance, Navigation, and Control Conference and Exhibit*, pp. 1–16, Aug. 2004.
- [36] B. E. Bishop, M. W. Spong, and W. M. Street, “Control of Redundant Manipulators Using Logic-Based Switching,” in *Proceeding of the 37th IEEE Conference on Decision & Control*, no. December, 1998, pp. 1488–1493.
- [37] W. Xu, S. Tso, and Y. Fung, “Fuzzy Reactive Control of a Mobile Robot Incorporating a Real/virtual Target Switching Strategy,” *Robotics and Autonomous Systems*, vol. 23, no. 3, pp. 171–186, Apr. 1998.
- [38] M. Yamada, C.-H. Lin, and M.-Y. Cheng, “Vision Based Obstacle Avoidance and Target Tracking for Autonomous Mobile Robots,” in *The 11th IEEE International Workshop on Advanced Motion Control*, 2010, pp. 153–158.
- [39] O. Namaki-shoushtari and A. P. Aguiar, “A Switched Based Control Strategy for Target Tracking of Autonomous Robotic Vehicles using Range-only Measurements ,” in *Proceeding of the 18th IFAC World Congress*, 2011.
- [40] D. Luo, W. Xu, and S. Wu, “UAV Formation Flight Control and Formation Switch Strategy,” in *The 8th International Conference on Computer Science & Education*, 2013.
- [41] M. Mehrandezh, “Navigation-guidance-based Robot Trajectory Planning for Interception of Moving Objects,” Ph.D. dissertation, University of Toronto, 1999.