1.1 INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are gaining wide acceptance as tools in various industries, in civil as well as military applications. Many UAV systems are expensive and require substantial amounts of personnel and equipment on the ground to support any mission. The deployment of an UAV involves risk and critical applications. These risks include damage to the airframe particularly during take off and landing, damage to the flight control system and damage to the mission payload. Damage of any kind to the flying hardware is naturally undesirable, however when the UAV is deployed in a remote location, damage completely nullifies any advantage in deploying UAVs. If, after the first flight, damage on landing prevents the UAV from performing further missions, UAVs become a liability. Risks on landing can be reduced by the use of experienced operators, with knowledge of the aircraft and landing techniques. Unfortunately there may not be an experienced pilot around when there is a need and keeping them ‘on-sight’ in a remote and potentially hazardous location may be prohibitively expensive.

It has been often said that commercial pilots earn their money in the first three minutes and the last three minutes of every flight. One possible and fairly obvious reason for this view is the dramatic increase in proximity of the ground at such times. UAVs, though unmanned, are generally not disposable items, particularly in domestic or commercial applications. In the process of testing various UAV airframes at DRDO laboratories and University
environment, it was observed that substantial amounts of time, money and effort went into the design and construction of a UAV airframe and its payload, but only seconds were required to destroy everything. Even highly experienced pilots have bad days or sometimes the weather conditions are not favorable or simply that too many things are happening at a time. The need for assistance in such critical moments was considered for this study.

In order to improve the profile of UAVs, it is desirable to lower the complexity of their deployment, specifically to minimize the risk of damage during the critical phase of UAV recovery. This research aims towards the Design and Development of Automatic Landing System approach to UAV deployment, where the operator is primarily interested in the mission destination and the results are obtained with only minimal interest in the operation of the UAV platform.

Truly autonomous operations are highly desirable for Unmanned Air Vehicle (UAV) applications. The UAV market is currently one of the rapidly growing sector in the aerospace industry. The role played by the UAV in Kosovo, Afghanistan and Iraq has strengthened its position as a vital combat tool. Unmanned Combat Air Vehicles (UCAV) has been under development for some time and confidence in the capabilities and advantages offered by unmanned operation has increased. Hence, the introduction of these vehicles into frontline service will be accelerated in future years.

The challenges presented to operators of UAVs are to integrate the UAV fleet with the piloted fleet while adhering to the tried and tested operational procedures already in place without abating the benefits of autonomy offered by UAVs. This is specially challenging in the Automatic Landing environment. With respect to the recovery of UAV operations this challenge raises two questions. First, is the determination of the most
effective navigational method to guide a UAV through the approach and landing phase considering the systems, procedures currently in place and the future military navigational goals and also the objective of seamlessly integrating the UAV fleet with the piloted fleet while attaining maximum autonomy. Second, is the determination of the best way to control a UAV through the approach and landing phase of a recovery.

1.2 OBJECTIVES OF THE RESEARCH

The main objective of this research study is the design and development of terminal phase flight control system for an Unmanned Air Vehicle. It is verified by software simulation and Hardware-In-the-Loop simulation environment. In particular, for aircraft autolanding problem, a methodology to practically eliminate the need for switching between glide and flare modes with the help of a newly developed concept called blending function is presented in the work. The objectives of the work in this thesis can be summarized as follows:

- To analyze the dynamics of the aircraft, develop a non-linear 6-DOF model for an experimental UAV.
- To design Autopilot using conventional PID controllers and Gain scheduling control strategy along with the selection of suitable scheduling variables for an aircraft autopilot.
- To design and develop a baseline controller using conventional and backstepping approach for automatic landing of an UAV.
- To design and simulate the blending function for landing phase of an unmanned air vehicle and interface the glide and flare path with the blending function.
- To explore the above blending function scheme for aircraft autolanding problem in normal and turbulence conditions using Conventional, Neural and Fuzzy Controllers.
- To develop a Hardware-In-the-Loop (HILS) platform for the implementation of the controller.

The scope of this investigation is shown in Figure 1.1.
DESIGN AND DEVELOPMENT OF TERMINAL PHASE FLIGHT CONTROL SYSTEM FOR AN UNMANNED AIR VEHICLE

- Development of six degrees of freedom model for an UAV
- Linearization of 6 DOF model
  - Longitudinal Model
  - Lateral Model
- Design of Autopilot
  - Lon. Autopilot
  - Lateral Autopilot
- Design of landing system
  - Glideslope Control
  - Flare Path Control
- Design of Blending function
- Interfacing with X-plane Simulator
- Simulation of Autonomous Landing during normal conditions and wind pattern using Conventional, Neural and Fuzzy Logic Controllers
- Hardware In the Loop Simulation
- Summary and Conclusions

Figure 1.1 Overview of the Thesis
1.3 LITERATURE SURVEY

There are two objectives in reviewing Aircraft Landing operating procedures and research related to this study. The first is to gain a better understanding of operating procedures and the current state of the art. The second is to provide a context for this current study in relation to that state of the art. In the lack of publications on Automatic Landing based UAV operations and related research the review has focused on piloted operations and related research. In general, there exists a distinct lack of publications in the area of UAV landing flight control systems and associated navigation systems. As a result, many of the publications reviewed were found not directly relevant to this study but did serve the purpose of an understanding of the UAV landing environment.

The literature review is completed comprising a critical review of relevant literature pertaining to the areas of Aircraft landing operations, Flight control and Navigation system in the area of UAVs and Intelligent control design techniques.

1.3.1 Literature Survey for Aircraft Landing Operations

Davies and Noury (1982) of Bell Aerospace, the manufacturer of the Automatic Carrier Landing System currently in service, presented a detailed technical description of the AN/SPN-42 system. This system is a carrier-based controller. Radar tracks the aircraft to determine its actual position and the system computes the aircraft’s distance from a stable horizontal coordinate system with origin at the average position of the intended touchdown point. This coordinate system is computed using the ship’s Euler angles, thus removing the effects of the ship’s motion on the
measurement of the aircraft's position in inertial space. Altitude and lateral position errors are generated based on the aircraft's range, altitude and desired glide slope. These error estimates are amplified and sent to an $\alpha-\beta$ filter which estimates the aircraft's acceleration, velocity and position errors. These estimates are then passed through a PID controller, which produce corrective pitch and roll commands required to direct the aircraft to and along the desired flight path. These commands are transmitted to the aircraft and implemented through the aircraft's Automatic Flight Control System (AFCS). The use of the Automatic Carrier Landing System requires that the Automatic Power Compensation System (APCS), or auto throttle, is used to maintain a reference angle of attack and to improve phugoid damping. Prior to 12 seconds to go to touchdown the aircraft is directed to the average, rather than the actual position of the touchdown point. This is done to reduce aircraft maneuvering. However, if satisfactory landings are to be accomplished, the aircraft must be directed to the actual touchdown point during the last few seconds. At the 12 second to go mark the target is faded from the average position to the actual position of the touchdown point over a 2 second period. A phase lead of about 2 seconds is applied to this new target, in effect predicting the position of the desired touchdown point; this is to compensate for the dynamic response lag inherent in altitude command control systems.

Descriptions of the design procedure, the associated hardware, safety features and control laws are included in this report. Problems encountered during the design of the system and the solutions developed to overcome these are presented.

Fitzgibbon and Parkinson (1989) presented a study in using GPS for use in automatic landing systems. Their study considered commercial applications as opposed to military applications. The advent of new empowering stand-alone sensors, such as the Laser Range Finder and GPS
has encouraged the adoption of onboard positioning and enhanced the navigation systems. These systems are currently recognized as instrumental in bringing about all the capabilities of an UAV to perform high precision tasks in challenging and uncertain operation scenarios. Several different methods have been proposed and flight tested, Shakernia et al (1996), Johnson et al (2001), Vasconcelos et al (2002) confirming the expected robustness and performance that can be achieved in the execution of specific maneuvers, such as landing or steering the vehicle to a desired target.

Airports are equipped with runway approaching systems that provide lateral and vertical guidance to aircrafts during the glideslope and final landing maneuver from ICAO report (1996). A common mechanism is the so-called Instrument Landing System that is composed of several radio beacons placed on the runway, allowing for vertical and lateral accurate guidance of the aircraft during the landing phase. Once the approaching maneuver starts, the ILS guides the vehicle to a certain height, referred to as the decision height, which depends on the airport’s ILS category and on the ILS based guidance system available onboard the aircraft. Different ILS categories provide different levels of autonomy to the aircraft runway approach and landing system. The most advanced one, ILS Category IIIc, allows for the automatization of the entire maneuver including guidance along the runway.

Despite the availability of those advanced landing systems, their complexity and the high cost involved on their implementation turn them into prohibitive solutions for small UAVs which should be able to land on any opportunity runway, grassy strip, or available road, resorting to low cost onboard navigation systems. Cunha et al (2006) and Frazzoli (1999) have described systems which provide vehicle’s automatic landing guidance and control algorithms with the actual vehicle’s linear and angular positions and
velocities, and dedicated modules allow for the integration of GPS/INS information with height data as acquired by a Radar Altimeter or Laser Range Finder mounted underneath the aircraft.


1.3.2 Literature Survey for Flight Control System

A study of the military standard MIL-F-8785C (1986) has been performed. This document contains the requirements for the aircraft’s flying and handling qualities, in flight and on the ground. It classifies various aircraft based on weight and maneuverability and specifies their handling qualities.

A textbook by Blakelock (1991) gives an in depth mathematical coverage of classical longitudinal and lateral autopilot design. Cook (1997), Stevens and Lewis (1996) contain detailed discussion of how to improve the stability of aircraft using the proportional feedback of aircraft states such as pitch rate to the control inputs. A good introduction to aircraft flight control systems is given in Nelson (1998). This has a very readable style and clearly describes the difference between classical and modern design techniques.

Ghalia and Alouani (1993) presented an automatic landing controller design based on Linear Quadratic Regulator/Loop Transfer Recovery (LQG/LTR) for a typical commercial airplane. The proposed controller was evaluated using the longitudinal motion of the linearized aircraft system and the simulation results showed that good system tracking of
the nominal trajectory was achieved either in the absence or in the presence of wind shear. Similarly Alonge (2005) employed the LQG/LTR control techniques to design a landing control system for an Unmanned Aerial Vehicle (UAV). The simulation study was carried out for landing with gust, rear or front wind and the results confirmed the robustness characteristics of the designed control system. Based on LQR controller a precision longitudinal control of an UAV for glidepath tracking was proposed by Kim et al. (2005). The performance of the strategy was validated with regard to atmospheric disturbance and simulation results showed that the proposed strategy maintained the touch down points (TDP) under wind turbulence.

Papadopoulos et al (1998) have addressed modern multi-variable techniques used in the development of a control law designed for the purpose of improving landing and braking performance as a total aircraft approach. The problem is to design a braking system that takes into account the all-axis aerodynamic and mechanical behavior of an aircraft at the point of touchdown and optimizes landing performance. The control scheme uses main wheel braking from the moment the main gear contacts the runway surface and the wheel velocities match that of the ground. The controller also uses the ailerons and main wheel brakes to aid in braking and the ailerons, rudder, nose wheel steering and differential braking to maintain directional stability.

Biju et al (2004) have addressed the automatic landing control of aircraft using the feedback linearization. The nonlinear aircraft equations are controlled using feedback linearization. The data of the F-16 is used herein. The aerodynamic coefficients, obtained from wind tunnel tests as a look up table, are approximated as polynomial functions of the Mach number and elevator deflection. The landing gear and flap data, along with the ground effects are added to the wind tunnel results to simulate the terminal phase of flight. The elevator is used to control the aircraft during landing. The elevator
dynamics is modeled as second order. The control task during approach is to maintain zero glide slope deviation from the three degree glide slope beam. An exponential flare is used, which inherits the sink rate at the end of the straight line descent. The results show that the aircraft meets the criteria of safe landing. This has been verified through parameters such as the touchdown sink rate, the positive pitch angle at touchdown, the velocity at touchdown, flight path angle at touchdown and the dispersions in the touchdown point.

Anthony J. Calise et al (2005) have surveyed the status of nonlinear and adaptive flight control, and summarizes the research being conducted in this area in the School of Aerospace Engineering at the Georgia Tech. A description of the controller architecture and associated stability analysis is given, followed by a more in-depth look at its application to a tilt rotor aircraft.

1.3.3 Literature Survey for Intelligent Control Design Techniques

Juang and Chio (2002) proposed a fuzzy-neural controller combined with a linearized inverse aircraft model to improve the performance of conventional automatic landing systems. A multilayered fuzzy neural network used as the controller provided the control signals during the aircraft landing phase and was trained based on the Back Propagation Through Time (BPTT) method. The error signals used to back-propagate through the controller was provided by the linearized inverse aircraft model. A commercial airplane was used for simulation study and the simulation results showed that the fuzzy controller achieved good landing performance in severe wind turbulence.
Malaek et al (2004) developed a fuzzy-neural control scheme for landing phase of a jet transport aircraft in the presence of different wind patterns. In this scheme, the outer loop utilized the fuzzy-neural controller based on Adaptive Network-based Fuzzy Inference System and the inner loop utilized the PID conventional controller. At the same time other three controllers named PID, Neuro based on Generalized Regression Neural Networks (GRNN) and hybrid Neuro-PID (its inner loop is PID and outer loop is GRNN) controllers were developed. Two different wind patterns named Strong wind (weaker than the JFK Downburst) and Very Strong wind (stronger than the JFK Downburst) were considered for the evaluation of their performance which classified at two levels named Level I (desired) and Level II (acceptable). Simulation results illustrated that all controllers satisfied the performance of level II in the presence of Strong wind but only ANFIS-PID controller satisfied the performance of level I. In case of Very Strong wind, the simulation results showed that only ANFIS-PID controller satisfied the Level I performance and only Neuro-PID controller satisfied the Level 2 performance. Consequently among the four controllers the fuzzy-neural controller achieved the best performance and extended the flight envelope of the aircraft.

1.4 ORGANIZATION OF THE THESIS

Chapter 2: Aircraft Dynamics

This chapter deals with the development of the Equations of Motion (EOM). To obtain the transfer function of the aircraft, it is necessary to derive the equations of motion of the aircraft. The equations of motion are derived by applying Newton's laws of motion, which relate the summation of the external forces and moments to the linear and angular accelerations of the aircraft. These equations are in general coupled, nonlinear and it is difficult
to obtain an analytical solution. Because of this non-linearity and compromise between the simplicity of analysis and accuracy of results, the equations are linearized by applying Small Perturbation (SP) theory. SP theory assumes that the motion following a disturbance is of small amplitude in all the disturbed variables. With this assumption and the approximation that the aircraft has a vertical plane of symmetry, the equations of motion are linearized and decoupled into two sets, one for longitudinal motion and another for lateral-directional motion.

Chapter 3: Development of Non-Linear Six-Degrees–of-Freedom Aircraft Model

This chapter deals with design of non-linear six-Degree–of-Freedom aircraft model for an experimental UAV using Aeronautical Simulation Toolbox. The developed UAV model contains Aerodynamic, Engine, Atmospheric, Gravity force, Actuator models, etc., for making a complete aircraft model. Before validating the model, a routine to determine trim settings for specified flight conditions were also written. The script developed to drive the linearization process is presented. This results in longitudinal and lateral state space representation matrices. The required transfer functions are generated from these matrices. Once the model had been trimmed, it was validated to check whether it actually behaved like an aircraft. The tests were performed to determine whether the model reacted correctly to control inputs.

Chapter 4: Autopilot Design

This chapter discusses about autopilot and its design rules along with its guidelines. It gives details about PID controllers and procedure for conventional and gain scheduling controller design for longitudinal and lateral autopilot modes are explained in this chapter.
Chapter 5: Automatic Landing System

In this chapter, a detailed description of landing systems geometry and conventional controller design procedure and backstepping method for glideslope and flare path control has been discussed.

Chapter 6: Blending Function

The details of method of switching from glideslope to flare command signals are carried out using Blending function. The primary objective of this research is to present a methodology to practically eliminate the need for switching between glide and flare modes by introducing the idea of Blending function by integrating the glideslope and flare controllers. This chapter also presents the interface between the X-Plane flight simulator and MATLAB®/SIMULINK®.

Chapter 7: Intelligent Landing Control

In this chapter, Aircraft Landing control based on neural networks and fuzzy modeling works are presented. Conventional automatic landing systems can work only within a specified operational safety envelope. When the conditions are beyond the envelope, such as turbulence or wind shear, they cannot be used. The simulation results are described for the automatic landing system of an UAV. Tracking performance and robustness are demonstrated through software simulations. Simulation results prove that the Neural and Fuzzy controller can successfully expand the safety envelope to include more hostile environments such as severe turbulence.
Chapter 8: Hardware-In-Loop (HIL) Simulation

The details of Hardware-In-Loop setup are presented in this chapter. In the hardware, the glideslope controller, Blending function and the flare path controller are embedded. The packed output from the MATLAB® is fed as input to the controller in the hardware and the calculations of the parameters like Range, Height, Elevator command and Sink rate are done. The calculated data is again fed back to the MATLAB and the obtained results are compared with the simulated results.

Chapter 9: Summary and Conclusions

This chapter deals with the highlights of the work done and the directions for future research.