A survey of autonomous landing techniques for UAVs

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Abstract— **Landing an aerial vehicle is a very challenging problem. Pilots spend numerous hours practicing touchdowns because of the risk involved during landing phase. Developing autonomous landing technologies have been an active area of research over the past decade. This paper presents a review of landing techniques ranging from GPS based landing to vision based landing techniques; from basic nonlinear to intelligent, hybrid and robust control. It is aimed at providing a broad perspective on the status of the landing control problem and controller design. The paper provides a comparison based on parameters such as type of the vehicle, assumptions made in the problem design, techniques used and efficacy of the algorithm in real world conditions.**

I. Introduction

Unmanned aerial vehicles (UAVs) are highly effective in remote operations. These vehicles have been used in several types of applications like surveillance [1], search [2], agriculture [3], [4] border patrol [5], scientific experiments [6], and mapping [7]. Communication, sensor and control techniques have evolved over the past few decade that has led to the development of a wide range of UAVs varying in shape, size, configuration, and characteristics. The common types of UAVs are fixed wing UAVs, Quad-rotors and helicopters at different scales (large UAVs or miniature vehicles or micro aerial vehicle). Fixed wing UAVs have a simple structure, fly at high speeds, and for a longer duration as compared to rotary wing UAVs. However, some of the fixed wing UAVs may require a runway for takeoff and landing, while those that can be either hand launched or through a catapult mechanism can be landed without a runway. On the other hand, rotary wing UAVs have an advantage of hovering, which is useful for monitoring some regions of interest. Rotary wing UAVs have agile maneuvering capability but at the same time they have high mechanical complexity, low speed and short flight range.

A. Landing Problem

UAV flight consists of different phases, namely, take off, climb, cruise, descent and finally landing. Most of the UAV autopilots have autonomous take-off (catapult and hand launched) and cruise but limited autonomous landing capabilities due to high risks and reliability issues. The accuracy of the landing must be high otherwise the aircraft may crash. Autonomous landing is one of the most challenging part of the flight. Landing must be done in a limited amount of time and space. Hence precise sensing techniques and accurate control is required during this maneuver.

A number of factors need to be considered for a smooth landing namely the type of landing (indoor or outdoor), visibility, type of terrain, wind disturbances etc. There are two aspects to landing namely sensing and control. Camera vision is a popular sensing technique to estimate the POSE (position and orientation) of the UAV whose information is used by the controllers. The type of controllers can range from simple linear control to complex techniques involving intelligent and hybrid control systems.

Figure 1 shows the block diagram of a generic landing control system. The system consists of four blocks namely sensors/navigation system, guidance controller, flight controller and type of the UAV. The sensors/navigation system mainly determines the POSE of the UAV. This information is fused for the flight and guidance controllers. The guidance controller generates guidance commands like change in velocity, acceleration and rotation to follow a desired trajectory. The flight controller takes the guidance command to generate the appropriate actuation commands according to the type of the UAV (VTOL or Fixed wing).

In this paper, we shall present different techniques pertaining to vision, control-based, guidance-based and recovery-based landing techniques and provide a comparison of these techniques.

B. Organization

The rest of the paper is organized as follows. In Section II we discuss the various landing controllers using GPS. In Section III we discuss the various techniques associated with vision-based landing.In Section IV and Section V guidance-based and recovery landing techniques are discussed correspondingly. Section VI involves the comparison of the above mentioned techniques and VII discussed the future challenges. We conclude in Section VIII.

II. Landing controllers

A typical landing system uses GPS (Global positioning system) and INS (inertial navigation sensors). The height measurement from the GPS is inaccurate and hence a close range sensors like radar altimeter, or barometric pressure sensor is also used in conjunction with GPS. However, GPS signals may not be always available and hence automatic landing may not be possible in many remote regions. In the case of unmanned helicopters GPS and INS systems

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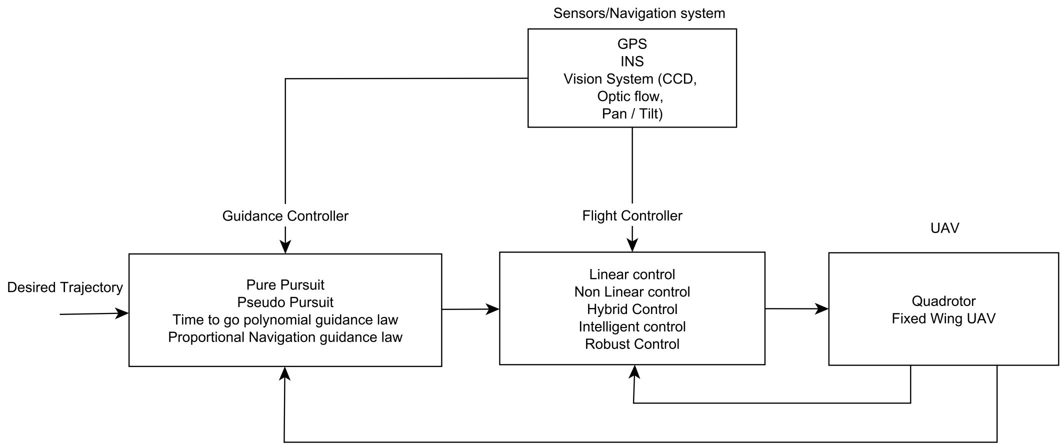

Fig. 1. A generic landing control system consisting of Sensor/Navigation system, Guidance and Flight controllers along with the type of the UAV

are suitable for long range and low precision flights but fall short for precise and close proximity flights [8]. Thus there is a need to integrate these systems for better accuracy and reliability.

A. PID control

The PID controller (proportional-integral-derivative controller) is probably the most used feedback design for linear control. Equation II-A shows the mathematical representation of a conventional PID controller where the control input vector u is expressed as a linear combination of error, error integral and error derivative between the desired and actual state variables.

$$u = K_p e + K_I \int_0^t e dt + K_D \dot{e} \tag{1}$$

Most of the aircrafts use the PID as a low level control technique. The other control techniques including the vision-based control are high level techniques that provide signals to the PID controller. Erginer and Altug [9] presented a PD controller design for a quadrotor vehicle that has different PD control loops for controlling quad-rotor altitude, pitch angle, yaw and its motion. Quad-rotor control using vision was also presented where the POSE was estimated using feature extraction technique. Linear control techniques like PID control can be a good choice if the dynamics of the system, especially the nonlinearity, is not known or poorly modeled. However, for aircraft motion, whose dynamics is readily available, PID control does not exploit the known nonlinearity in its control architecture and thus usually leads suboptimal performance. There are many vision-based landing algorithms that also use simple PID control loops as position, velocity and altitude controllers. Vision-based landing techniques are discussed in section IV.

B. Nonlinear Control Techniques

An aircraft model can be either a linearized or nonlinear aircraft model. In a linearized model, the longitudinal and lateral dynamics of the aircraft are decoupled which allows the use of separate controllers and control loops. Nonlinear control techniques such as feedback linearization, sliding mode control and backstepping control designs are often used for nonlinear aircraft model [10].

1) Feedback Linearization: Feedback linearization is a technique used for controlling nonlinear systems. It attempts to introduce auxiliary nonlinear feedback in such a way that the system can be treated as linear for the purpose of control design. Prasad and Pradeep [11] used this technique for landing control of a fighter aircraft. Voos and Nourghassemi [12] proposed a stabilized flight and landing strategy for quadrotor UAVs where they use the nonlinear feedback linearization technique to linearize and decouple three out of the six degrees of freedom. Burchett [13] applied feedback linearization to vehicle point mass dynamics to control the approach and landing of a reusable launch vehicle. This resulted in a linear system with inputs that were combinations of lift, drag and bank angle. By applying a simple aerodynamic model, lift and drag were mapped to negative z axis acceleration and speedbrake commands. Direct application of feedback linearization requires second and third order derivatives of uncertain aerodynamic systems which does not guarantee stability. To overcome this flight dynamics can be separated into slow and fast dynamics with sufficient timescale separation [14].

2) Sliding mode control: Sliding mode control technique is a nonlinear control technique that changes the nonlinear dynamics by application of a discontinuous control signal. In this technique, trajectories are forced to reach a sliding manifold in a finite amount of time and remain at that manifold for all future time. These trajectories in sliding mode control are defined as solutions to a set of sliding functions where the number of variables to track the trajectory should be equal to the number of available control inputs [15]. The main issue with sliding mode control is chattering and high control demand. Therefore, appropriate selection of sliding functions and reaching laws needs to be designed.

3) Backstepping control: Backstepping control is another nonlinear technique which can be used for designing a landing controller. The backstepping approach provides a recursive method for stabilizing the origin of a system in strict-feedback form. In such a system the designer can start at a basic known stable system and "back out" new controllers that progressively stabilize each outer subsystem. For autonomous landing of a UAV the subsystems can be rotation and linear translation subsystem [16]. Using the backstepping approach one can synthesize the control law for forcing a system to follow a desired trajectory. Ahmed and Pota [17] presented an application of backstepping controller for landing of a rotary wing UAV (RUAV) using a tether. This approach was extended in [18] where the backstepping-based controller takes advantage of the "decoupling" of the translation and rotation dynamics of the rigid body, resulting in a two-step procedure to obtain the RUAV control inputs. Lee and Kim [14] proposed a flight and landing control using backstepping along with neural networks where the backstepping controller tracked the angle of attack, side slip angle and roll commands assuming that aerodynamic model is completely known. Yoon et al. [19] proposed an adaptive backstepping controller design for aircraft landing with wind disturbance and actuator failures by the use of hedging techniques. Nonlinear six degree of freedom aircraft model was considered for the design of the backstepping controller that tracked a desired glide slope towards the runway. In order to estimate the modeling errors of aerodynamic coefficients in the nonlinear model, the adaptive parameter estimation of the nonlinear function was adopted.

C. Intelligent Control Techniques

Intelligent control is a category of control technique that uses various artificial Intelligence computing approaches like fuzzy logic, neural networks, and machine learning.

1) Fuzzy Logic: Fuzzy logic is a form of many valued logic. It handles the concept of partial truth, where, the truth value may range from completely true to completely false. Fuzzy control system is a system that makes use of fuzzy logic. It accepts analog continuous input values ranging from 0 to 1 instead of discrete values 0 and 1. The process of converting an input value to a fuzzy value is called "fuzzification" [20]. Fuzzy logic is used in the landing problem as it can accommodate nonlinearlities due to aerodynamics, actuators, sensors, and environmental disturbances. Also fuzzy logic controllers can be combined with conventional controllers like PID to model the system in a more realistic manner. Nho and aggarwal [21] developed a PD type of fuzzy logic controller and tested it on simulations using both linear and nonlinear models. Miguel et al. [22] presented a fuzzy logic based UAV landing using 3D position estimation.

2) Neural network-based control: Neural network-based control basically involves two steps: system identification and control. Neural networks have the ability to learn. Given a specific task to solve, and a class of functions $\mathfrak{F}$, learning means using a set of observations to find $f \in \mathfrak{F}$ which solves the task in some optimal sense. Malaek et al. [23] addressed the problem of designing an intelligent autolanding controller in the presence of different wind patterns to expand the flight safety envelope. Four different types of controllers were designed namely, PID, neuro, hybrid neuro PID and ANFIS-PID [24]. Neuro controller was designed to control the aircraft through glide and flare modes. Hybrid neuro controller was designed to handle the aircraft in very strong wind pattern. Fuzzy logic was used as it allows the development of a model free system.

D. Hybrid Control Techniques

A system that exhibits both continuous and discrete behavior is a hybrid system. State of a hybrid control system is defined by a set of continuous variables and a discrete control mode. In order to perform an autonomous landing a sequence of complex tasks must be performed, especially if there are obstacles on the runway. Koo and Sastry [25] presented a hybrid control design for the landing problem by modeling the outer-inner loop of the vehicle as a hybrid system. A pack controller controlled the discrete state of the system based on the continuous state. The hybrid controller encoded the switching sequences for the phases in the landing scenario.

E. Robust Control Techniques

Robust control methods explicitly deal with uncertainties in control design. A controller designed for a particular set of parameters and assumptions is said to be robust if it works well under a different set of assumptions or uncertainties also. One of the robust control techniques used for UAV landing is the mixed H_2/H_∞ control technique. H_2 control involves minimizing the H_2 norm of a system. H_∞ methods treat the control problem as a mathematical optimization problem and aims to design a controller that solves this optimization problem. Mixed H_2/H_∞ is a control method which combines the advantages of both H_2 and H_∞ systems to achieve a robust design. The H_2 component achieves good dynamic response, but it is potentially weak in robustness characteristics and the ability to counteract disturbances. The H_∞ norm is the worst case gain of the closed loop transfer function. Thus minimization of this norm is equivalent to minimization of the worst case (gain) situation on the effect from disturbance to the controlled output. This method results in a controller that is robust to disturbances but is relatively weak in performance measures used to assess controllers such as settling time, energy expended etc. Liao et al. [26] proposed a robust fault tolerant controller that can handle external wind disturbances and control failures by employing H_2 control technique on a linearized aircraft model. Shue and aggarwal [27] proposed an automatic landing system for a liniearized aircraft using a mixed H_2/H_∞ control. Wang et al. [28] used this approach to address the landing problem of a flying wing UAV so that it tracks its landing trajectory even under the influence of uncertainties and disturbances. H_2 performance variables were formulated as an LQG problem to meet efficient dynamic responses and H_∞ was used to eliminate the disturbance due to ground effect and atmospheric disturbances.

III. Vision-based Landing

Computer vision is used in the feedback control loop of an autonomous landing system. Use of vision in the control loop is especially suited for problems where the landing pad is in an unknown location or non-stationary (the deck of a ship). There are a number of vision-based control techniques for helipad detection, tracking and landing (both indoor and outdoor). Classical vision-based target tracking and landing focuses on object recognition using edge detection techniques. Although vision provides a natural modality for object detection and landing, but it can only sense the changes due to the applied forces not the forces themselves. Hence vision-based techniques are integrated with conventional control techniques for a good and robust landing design.

A. Indoor landing using infrared

Indoor landing involves landing in a controlled environment with less environmental disturbances as compared to outdoor landing. Wenzel et al. [29] use a Wii remote infrared camera for their visual tracking approach with the control algorithm running on an onboard microcontroller. They track a pattern of infrared spots by looking downwards with a fixed camera. The integrated circuit provides the pixel position of each spot at a high frequency. The estimated pose is used in various integrated PID control loops to control the vehicle motion.

B. Outdoor landing

Outdoor Landing is a more challenging problem due to the presence of external disturbing factors such as wind, visibility, etc. The main part of any vision-based landing is to detect the helipad using object detection or pattern recognition techniques. This can be done using a number of approaches as given below.

1) Image segmentation: It involves partitioning an image into sets of pixels and assign a label to every pixel in the image such that pixels with the same label share some visual characteristics. This can then be used to identify lines, object boundaries and curves in the image. Thresholding is one of the easiest method of image segmentation that converts a gray scale image to a binary image.

2) Image moments: In image processing, image moment is the weighted average of the image pixels' intensities, or a function of such moments. These usually have some special characteristics and interpretation. They are generally used to describe objects after segmentation.

3) Monocular vision: It is a technique in which each eye is used separately unlike binocular vision thus increasing the field of view but limiting the depth perception.

4) Stereo vision: It is the process of extracting 3D information from images. The information about a scene from two vantage points is compared, after which 3D information can be extracted by examination of the relative positions of objects. Pan et al. [30] used a combination of monocular and stereo vision to estimate approach angle and relative height of UAV with the use of Hough transform, RANSAC (Random Sample Consensus) [31] algorithm and vanishing line geometry. Sereewattana and Ruchanurucks [32] proposed depth estimation of markers for landing control using stereo vision. A single camera is used to capture two consecutive ground images for simulating a pair of stereo images. The markers consisted of four different colored circles. Their positions were extracted using Hough transform. The height between the UAV and the markers in world coordinates was then determined. In [33] vision was integrated with low level postural control to achieve precise autonomous landing of a helicopter. The vision algorithm consists of preprocessing, geometric invariant extraction, object recognition and estimation. The landing target is detected and extracted using thresholding and filtering technique. Invariant descriptors are calculated based on moments of inertia of the object. Height of the helicopter can be calculated using differential GPS and the pose of the helipad in helicopter body frame is calculated using x and y coordinates of the camera in image plane, image resolution and field of view of the camera in x and y directions respectively. The state estimates were sent to a behavior based hierarchical controller where the control problem was partitioned into a set of loosely coupled behaviors with each behavior being responsible for a task. This work was further extended in [34] where, the problem of tracking and landing on a moving target using an autonomous helicopter was addressed. The target was detected in a similar way as [33] and tracked using a Kalman filter by modeling the equations of the target as a linear system with the assumption that target moves only in one dimension. A variant of thresholding technique called adaptive thresholding was used by Lange et al. [35] to detect a landing pad and land a multirotor UAV using vision in GPS denied environments. Daquan and Hongyue [36] proposed a vision-based navigation algorithm using extended Kalman filter (EKF) to estimate aircraft's POSE where the inputs to this were parameters like image gradients of centerline and threshold bar of runway lighting, longitudinal and lateral mean of the image coordinates of observed airport lights.

Shakernia et al. [37] modeled the vision problem as a special case of ego motion estimation problem. Ego motion estimation involves estimating a camera's motion relative to a rigid fixed scene. Position and velocity of the UAV relative to landing pad are estimated by discrete and differential versions of egomotion estimation respectively. Estimated motion and structure from vision as a sensor is used in the control loop where the controller is a general trajectory tracking controller. In this case the UAV was asked to track a fixed point at the desired configuration above the landing pad. In [38] detection using infrared images was performed. The temperature difference between the target and background plays a key role in finding the target object. To detect, a high emissivity black powder is spread on the object. Barber et al. [39] addressed the autonomous landing problem for MAV (miniature/micro air vehicles). The HAG is determined using optic flow by relating the flow of features across an imaging array. The number of pixels that a given object moves in the imaging plane can be combined with MAVs IMU and GPS data to determine HAG. The optic flow method was also used by Herisse et al. [40] to perform the landing of a VTOL on a moving platform. The position and attitude estimates provided by the vision algorithm cannot be used directly by the controller as they are not robust. For example, the field of view can be temporarily occluded and the illumination conditions might change drastically within a distance of a few meters. Merz et al. [41] developed a navigation filter based on a Kalman filter that was used to fuse highly accurate vision system estimates with inertial data provided by the onboard accelerometers and high rate gyros. This filtered out a large part of noise and outliers and also these filters made a smooth landing possible even when the vision system was blind. Miller et al. [42] proposed a method to land using image registration. They used information about the terrain surrounding the runway from different scales and distances instead of the visual features of the runway itself. Geometric features are obtained which are approximately linear indicators of the quantities to be measured. The course deviation of the UAV can be estimated from the camera model and registered image is used as an input to a linear feedback control loop.

IV. Guidance-based landing

Guidance refers to the determination of desired trajectory from vehicle's current location to a target, as well as direction, rotation and acceleration for following that trajectory. Proportional guidance and pursuit guidance are two of the widely used laws for UAV guidance. Proportional guidance aims at maintaining a constant angle between the LOS and the target whereas pursuit guidance aims at generating commands to make the velocity vector of the UAV point towards the target. There are two main types of pursuit guidance laws namely pure pursuit and pseudo pursuit. Pure pursuit guidance law leads the UAV towards a true target, while the pseudo pursuit guidance law generates a guidance command to track a virtual target. As the virtual target moves to the true target, the UAV finally arrives at the true target [43]. Bang et al. [44] designed a guidance law for automatic landing of UAV using vision sensors for both fixed wing and rotary wing UAV. The method iteratively estimated a time-to-go until target intercept and modified the acceleration command based upon the revised time-to-go estimate. The time-to-go estimate depends on the position, the velocity, and the actual or real time acceleration of both the vehicle and the target.

V. Recovery Landing Techniques for small UAVs

Traditional landing of a fixed wing aircraft undergoes phases like glide slope and flare which require a large area. To accurately determine landing coordinates high precision differential GPS (DGPS) and radar altimeter may be required which are costly compared to the cost of small UAVs. In addition, the small UAVs have limited payload capacity. Net recovery landing methods have been (in particular vision-based net recovery methods) proposed to land UAVs in restricted areas. Kim et al. [45] proposed a fully autonomous vision-based net recovery system for a fixed wing UAV. It consisted of a ground vision system whose aim was to detect a recovery net during landing and provide longitudinal and lateral bearing angle to the vehicle. These angles were calculated according to a guidance law based on the net position. Pursuit guidance law was used for longitudinal guidance and a nonlinear pursuit guidance law for lateral guidance in order to land the UAV.

Another approach for net recovery is to divide the landing phase into spiral descent and final approach [46]. The aircraft aligns along the flight path angle towards the approach direction by the end of the spiral descent phase. The aircraft is guided from approaching waypoint to the recovery net using a pseudo pursuit guidance law. Approaching waypoints were generated using a cubic polynomial in the guidance law. Another landing technique in this category is "arrested landing" which involves catching a wire on board the ship with a deployed tail hook, bringing the aircraft to a quick stop [47]. Huh et al. [48] proposed a vision-based automatic landing system using a dome-shaped airbag for small UAVs. Color and shape based detection vision algorithms are applied for robust detection under varying lighting conditions due to dome's isotropic shape and distinctive color.

VI. Comparison

Landing is one of the most challenging maneuver. Choosing an appropriate landing technique or control law is thus a very crucial task. Various landing techniques and laws were discussed in previous sections. The selected landing technique depends on various factors like type of UAV, environmental assumptions and aerodynamic constraints taken into consideration etc. Linear control techniques such as PID control and nonlinear feedback linearization are useful when the aerodynamic model is completely known. However, there are uncertainties associated while designing the model and hence sophisticated control techniques like mixed H_2/H_∞, fuzzy logic controllers are designed but they have been modeled for linearized aircraft which limits the motion to a single dimension.

A controller based on vision and neural network was proposed in [49] where the pilot action was modeled using neural network. The constraint with most of the neural networks is that they can be reliable when landing conditions fall within the range of trained data set, thus a significant amount of training data is required for sufficient reliability. Fuzzy logic control can be combined with more sophisticated nonlinear techniques instead of simple PID, PD control to introduce randomness in the system. This can be used to model a more realistic system as it helps to take random environmental factors into account.

Vision-based landing techniques do not rely on GPS and estimate POSE using computer vision techniques described in Section IV. During the last 50 cm before touch down the vision system is often blind due to two factors

1) Shade of the aircraft covers part of the pattern at touchdown.

Ref.	Controller Details	UAV type	Additional Characteristics	System Details
[9], [21]	PID [9], PD with fuzzy logic [21]	VTOL	None	• 6DOF simulations • Pitch, roll and altitude control
[11], [12], [13]	Nonlinear Feedback Linearization	Fixed Wing(F-16 Model) [11] [13], VTOL [12]	Actuator dynamics and aerodynamic drags	• 3DOF aircraft Model • Ground effect is studied
[15]	Sliding Mode Control	Fixed Wing(HARV Model)	None	• 6DOF Nonlinear Model • Simulations only • Lyapunov stability criteria • Comparison with PID controller
[14], [17], [18]	Backstepping and Neural Networks	Fixed Wing (F-16 model) [14],Rotary UAV [17] [18]	aerodynamic model uncertainties	• 6DOF Model • Backstepping control • Adaptive Neural Networks for aerodynamic modeling error under uncertainties • Flapping correction and servo dynamics
[25]	Hybrid Control	Simulated for a general UAV	Runway traffic	• Landing as a sequence of tasks • Switching strategy between controllers • Design Correctness analyzed by a reachability computation

TABLE I
COMPARISON OF CONTROL BASED LANDING TECHNIQUES USING GPS

2) When the distance of the camera to the pattern is very small it is very hard to keep the pattern in picture.

This effect has not been considered in the discussed literature except [41].

Vision-based techniques have been combined with guidance-based techniques and control techniques to achieve a robust control design. Since Proportional guidance aims at maintaining a constant angle between the LOS and the target, it can be used to track and finally land on a moving target where as pursuit guidance is more appropriate for guiding to a stationary target since it aims at pointing the velocity vector of the UAV to the target.

Airbag based recovery landing fares well than net based landing especially in the presence of cross winds. The isotropic shape of the dome allows the airplane to approach from any direction to avoid crosswind unlike net based landings.

Table I and Table II provides a comparison summary of some of the main control based and vision-based landing techniques discussed in literature. References of the main papers and similar papers are also given in the tables.

VII. FUTURE CHALLENGES

A variety of landing controllers were discussed and compared in literature. Robustness of a controller is one of the key issues in order to fully assess a controller. This requires more realistic flight testing other than numerical simulations and also an analysis on the theoretical stability of the controller. It is thus of great importance to design a robust controller that does not fail all of a sudden in unforeseen situations like GPS failure but the controller must degrade gracefully. One of the ways to achieve this is designing a human in the loop interface in the control system which would ensure that controller does not fail suddenly in unforeseen situations like sensor failures. Also, from the literature discussed, it is clear that there does not exist an ideal sensor for landing. vision-based sensing techniques cannot be solely relied due to blindness of the vision system near the end of the landing phase, environmental conditions where the vision system might not work like fog, mist etc. Although HAG estimation which is the one of the key parameters in a good landing can be improved by using

Ref	UAV Type	Equipment	Techniques	Assumptions	Testing
[33], [34]	VTOL	• Downward CCD camera • ultrasonic sonar and INS	• Invariant moments • Kalman filter based tracking	• Helicopter is in Hover • Target tracking in one dimension	Flight Tested
[39], [40]	MAV in [39], VTOL in [40]	• Optic flow sensor • IMU, GPS • Barometric pressure sensor	Optic flow sensor and barometric altimeter based HAG estimation	None mentioned	Tested in different wind conditions
[41]	VTOL	• CCD Camera mounted on a PTU • Accelerometer and angular rate gyros	• Contour extraction • Kalman filter fusion	Special Landing pad with Reference Pattern	Flight Tested with wind (upto 10m/s).
[29]	VTOL	• Wii Remote IR camera • IMU, GPS and compass module, Pressure sensor	Pattern Analysis to retrieve pose from the camera and IMU	• Indoor landing only • Requires accurate roll and pitch estimation	Tested with hardware .
[38]	Not specified	• Black object on the landing target • Infrared thermal imager, GPS and INS	• Recognition from infrared images • Affine moment invariants	'T' model based landing target	• Only simulations
[30], [32], [36]	Not specified	Two Camera sensors	• Monocular, stereo, and machine vision • EKF, Hough Transform, Vanishing Geometry, RANSAC Algorithm	Markers used on Helipad in [32]	Simulated results

TABLE II
COMPARISON OF VISION-BASED LANDING TECHNIQUES

sensors like a laser range finder, there is a need to design a flight tested robust controller that uses a combination of sensors to land in different environments and unforeseen conditions.

VIII. Conclusion

An extensive review of various landing techniques using a number of control and vision-based techniques was provided for different types of aircraft. Most of the control based landing techniques are evaluated using simulations which minimizes their applicability in real-hardware. However, most of the vision-based control techniques have been tested on real hardware platforms and have shown promise. For the use of robust control laws various environmental factors and aerodynamic constraints must be taken into account.

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