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GUIDANCE AND CONTROL OF AUTOMATIC SHORT LANDING WITH STEEP GLIDE SLOPE FOR UAV

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Abstract

This paper presents the guidance and control law designed for the automatic landing sequence of a tactical-level UAV that is required to follow a steep landing slope. The automatic landing system consists of a precision location tracker and a flight control computer.
The guidance and control law is developed to filter and switch between navigation signal sources and generate control surface commands to keep the UAV within the boundaries of its landing trajectory. A two-stage flare maneuver is suggested to overcome difficulties associated with having to maintain a steep approach slope for landing in mountainous terrain. The performance of the automatic landing system was verified through the Hardware-In-the Loop testing and flight tests, which confirmed that the two-stage maneuver assured the UAV to attain high levels of touchdown accuracy and a sufficiently low vertical speed to satisfy its landing requirements.

1 Introduction

Automatic take-off and landing (ATOL) is a basic function of the recent UAS to operate and to reduce accidents during take-off and landing phases without a skillful pilot. From the report of FAA [1], human factor is a main cause of 67% in accidents of Predator UAV operating with manual landing by pilot whereas 21% in Shadow UAV with automatic landing system.
Even though the ATOL system subsists, Most of UAVs require a run-way or flat area and no obstacles near landing zone. The operational availability decreases in mountainous area due to limited approach slope angle and landing zone. KUS-FT is a tactical UAV which is optimized for operation in mountain area where steep approach angle and precise automatic landing capabilities are required. In this paper, The UAV and the ATOL system are introduced with results of the guidance and control design and testing.

2 UAV Systems

2.1 UAV Specification

The KUS-FT UAV had been developed for the reconnaissance and surveillance (R&S) mission which is suitable for operating in mountainous areas. It is also the first UAV that received the military aircraft airworthiness type certification from the Korean government with special characteristics:

- Automatic catapult take-off
- Automatic short slope landing
- Emergency parachute recovery
- Remote engine starting
- In-flight engine restarting
- Multi UAV control (Mission Sustainment)
- Dual flight critical system
- Replaceable landing gear/skid system

Fig. 1. KUS-FT tactical UAV

2.2 Concept of Landing Operation

The Concept of the automatic landing operation is represented in Fig. 2. The UAV starts to fly to the landing standby waypoint when an operator engages "Auto Landing Mode". After arriving to the waypoint, the UAV descends until reaching the reference orbiting altitude and follows the landing approach trajectory after checking the landing entry conditions. This position is called as the Initial Approach Fix (IAF) for the reason that the aircraft changes configuration for landing and prepares final approach procedure. The operator is able to modify the landing plan and send wave-off command any time before the UAV passes the 1st flare position.

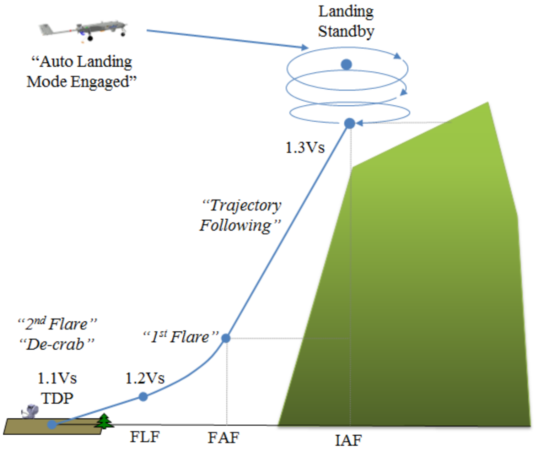


Fig. 2. Trajectory of the steep landing

During the automatic landing, Integrated Flight Control Computer (IFCC) generates the reference landing trajectory internally and follows the trajectory to the Touch-Down Point (TDP). In the course of approaching, it makes a decision of the automatic wave-off through checks of trajectory deviation and system status. If the systems are normal condition and the UAV follows the trajectory well, two step flare maneuverings are performed after passing the Final Approach Fix (FAF) position. Because the glide path angle during initial approach is too high (11deg) for this UAV comparing to general aircrafts. (Usually 2~3deg for normal, 4deg for engine fail condition) [2], the flare maneuvering is separated with two steps, i.e., 1st flare reduces path angle to meet the vertical touch down speed requirement related with limitation of the landing gear and the airframe structure. 2nd flare decreases the landing shock maintaining the small touchdown position error simultaneously. The de-crab maneuver to anticipate to the cross-wind effects is activated during the 2nd flare phase. The engine stops automatically to protect propeller and a ground arresting-hook system captures the UAV after touchdown. The position of the engine stop is determined by the time response of the controller and duration of the propeller's rotation from the engagement of the engine stop command.

2.3 ATOL System

The ATOL system of UAV is dependent on a concept of operation and requirements of the operational environment. DGPS, Pseudo GPS, Laser, Radar and Vision solutions are typically used for the ATOL. In this research, the ground based active radar tracking system is used to measure accurate position of the vehicle. Fig. 3 shows a diagram of the automatic landing system. The Ground Precision Location Tracker (GPLT) tracks a beacon radar signal of the Airborne Precision Location Tracker (APLT) which is installed in front of the UAV. The relative position data(X, Y, Z) from the Reference Point (RP: Generally center of the runway) is transmitted to the IFCC through the airborne data link. The IFCC processes relative position information measured by PLT and control the vehicle to the touch-down point with the control law (CLAW).

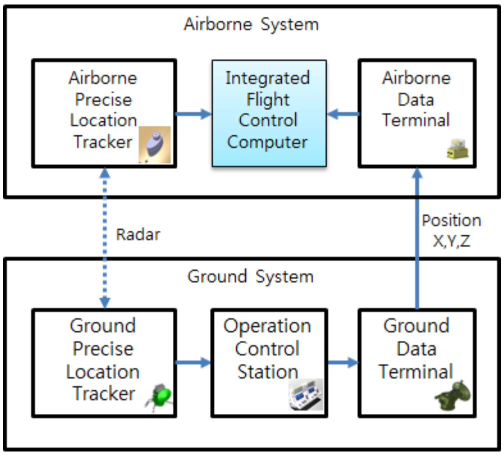


Fig. 3. Automatic landing system of the UAV

2.4 Flight Control Software

The flight control software includes signal processing, fault management, operation and flight mode management and control law. The control law is the key CSCI (Computer Software Configuration Item) including functions as below: [3]

- Vehicle State Management (VSM) that processes onboard sensor data e.g., air data, GPS/INS, PLT, and Engine Control Unit (ECU).
- Flight Mode Management (FLTMM) that manages flight operational modes including emergency procedures and various autonomous flight modes.
- Guidance (GUID) that generates autopilot commands to track a route and waypoints.
- Flight Control (FLTCTRL) that stabilizes attitude of the vehicle and follows guidance command or manual command e.g., roll/pitch, heading, speed, and altitude.

Table 1 shows major functions of the CLAW related with the automatic landing.

Table 1 Functions of CLAW components related with automatic landing

Component	Function Requirements
VSM	• Filtering of PLT data • Position data fusion/switching • Coordinated transformation • Landing direction check • Weight-On-Wheel(WOW) decision
FLTMM	• Auto landing sequential diagram • Landing trajectory generation • Approach decision • Auto wave-off decision • Engine stop decision
GUID	• Waypoint management • Guidance data calculation • Lateral landing guidance • Vertical trajectory guidance
FLTCTRL	• Path control • Altitude/Speed control • Controller switching • Envelope protection • De-crab control

3 Guidance and Control for Landing

3.1 Sensor Data Processing

The source of position data should be selected properly according to the system status and landing procedures in VSM. Table 2 shows general properties of data sources in terms of the altitude measurement (GPS/INS, Air data, PLT). The availability of the Air Data System (ADS) is the highest value comparing to other data sources but it has low accuracy and low consistency by effects of weather and time variations. In contrast, The GPS/INS provides high consistency but is not able to provide the accurate position data for the automatic landing without the differential GPS. The radar-based relative position measurement system used in this research (PLT) provides high position accuracy (centimeters) but it is affected by packet loss, time delay and alignment bias errors.

Table 2 Property of available altitude data

Property	Air data	GPS/INS	PLT
Accuracy	Low	Medium	High
Availability	High	Medium	Medium
Update Rate	Medium	Medium	High
Consistency	Low	High	Medium

The IFCC should filter signals of several sensors and select appropriate data source according to landing scenario.
The common coordinates is required to minimize discontinuous effects of switching and filtering. The World Geodetic System 1984(WGS84) coordinate is implemented. (well known as a coordinate system for GPS). [4]
The IFCC also uses Low-Pass Filter (LPF) to eliminate noise effects induced by packet loss of data link or discontinuous digital data format.
The position measured by PLT is a relative XYZ referenced by the fixed RP. But in real world, UAV lands from the different approach direction according to the wind condition. Therefore, the IFCC calculates the landing direction using geometry information with the landing standby point and position of GPLT and TDP.

3.2 Auto Landing Mode Management

The automatic landing mode management is designed with 6 stages. If the operator engages the automatic landing mode, UAV flies to the landing standby waypoint and generates landing trajectory internally, descends until desired altitude. During orbiting, the UAV checks conditions of the initial approach. If it satisfies the entry requirements (altitude and heading) flaps are extended and the autopilot control loop is changed from the mission control scheme to the landing control scheme. Because during the mission flight, the pitch control loop is used as an inner loop of the speed control and the throttle is used for the altitude control on account of stability for maintaining airspeed rather than altitude. However, during landing, the accuracy of landing trajectory and touch down point are critical to decide success of landing.

Table 3 Automatic landing phase & action

Phase	Action
Go To Landing Standby WP	Waypoint guidance Orbit direction decision
Orbit Descent	Spiral descent Generation of landing trajectory Flap angle decision
Initial Approach	Landing entry condition check Flight path control Changing of speed control Flap extending PLT selection
Final Approach (1st Flare)	Maintain landing trajectory Landing window check
Final Landing (2nd Flare)	Maintain landing trajectory Block of wave-off Gradually speed reduction Decision of de-crab altitude De-crab and de-rotation Engine stop decision Nose steering control
Landing Wave-off	Flap retraction Straight climb with WOT Safety altitude check Go to the landing standby WP

Once the UAV passes the FAF, the landing wave-off mode is not allowed and the UAV starts to decrease speed from 1.3Vs to 1.2Vs. Nearby the TDP, 2nd flare altitude is determined by descending rate and the vehicle performs de-crab and flare maneuvering to reduce touchdown vertical speed.

If the UAV gets out of reference trajectory or malfunction of the system occurred or received the manual landing abort command, the landing phase transits to the landing abort phase. The UAV retract flaps, climb to the safe altitude via Wide-Open-Throttle (WOT) and flies to the take-off standby point in landing abort phase. If the UAV arrives at the position and altitude, it flies to the above of the TDP. After that, the UAV returns to the landing standby point to wait succeeding commands.

3.3 Landing Guidance

To meet the requirements of the automatic landing for short landing area and steep approach slope more than 11degrees, two step flare trajectory was suggested. From modeling and simulation, initial approach phase is the most important to make successful landing. Consequently the landing procedure including switching of controller scheme, flap extension and sensor selection logics is designed to reduce distance error at the initial approach phase.

Fig. 4 shows the geometry of the cross track guidance.

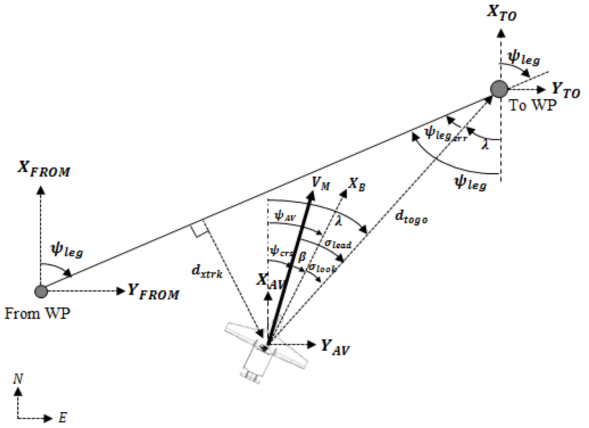


Fig. 4. Geometry of lateral guidance

The landing approach procedure is not critical for general automatic landing on the runway. But short landing performance is affected by approach maneuvering and procedure due to lack of time to converge cross-track error. The landing approach procedure is designed considering critical altitude, time delay of the level-turn, duration of flap extension and response of the path control, and PLT alignment error. Fig. 5 shows the approach procedure of the landing that used in this research. The relative heading to the approach direction (ψ_d) is designed from the obstacle requirement near landing standby point. (The shape of the circular loitering trajectory in 3D is similar with spiral configuration at the final)

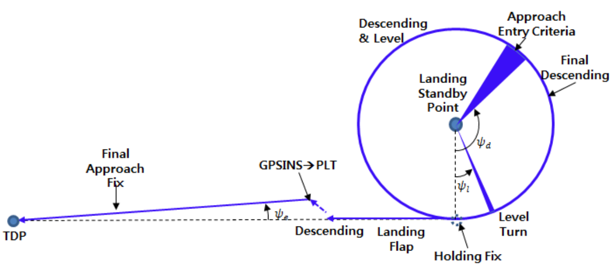


Fig. 5. Landing approach procedure

The longitudinal control loop is consistent with the path angle controller including pitch control loop as an inner loop and speed control loop with throttle. (Fig. 6) For short landing operation, 1st flare maneuvering changes large path angle (6~7deg) but requires accurate trajectory following performance simultaneously. The throttle feed-forward term is added to remove the overshoot during 1st flare and to reduce vertical deviation from the reference landing trajectory without loss of altitude.

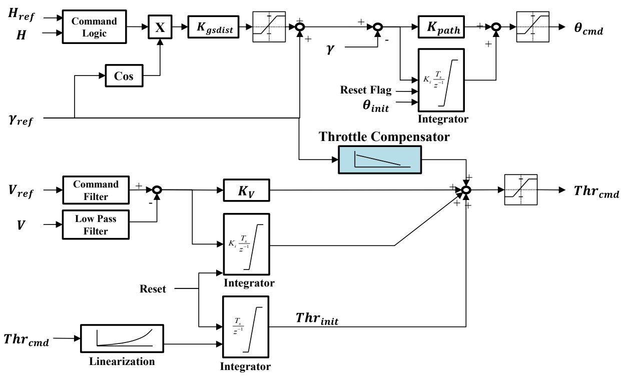
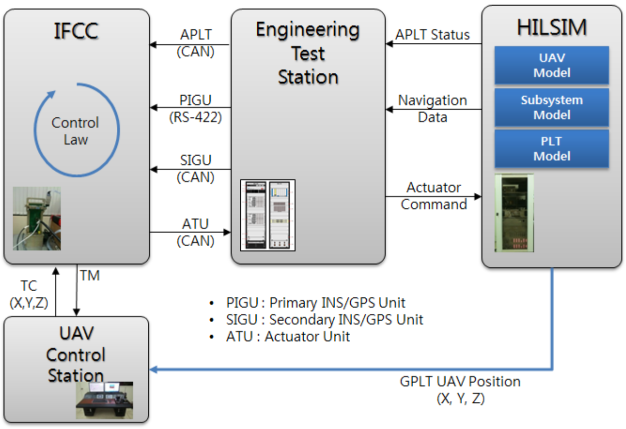


Fig. 6. Structure of longitudinal control

4 Verification

4.1 HIL Environment

The Hardware-In-the-Loop (HIL) Test is a well-known method to verify performance and reliability of a system prior to flight test. [5] The CLAW including auto landing mode is embedded into the IFCC and receives sensor data through the airborne system interfaces from the Engineering Test Station (ETS) and mission planning data from the UAV Control Station (UCS). Flight dynamics, subsystem model including navigation equipment, engine, air data system, and PLT model run in the HILS Engineering Simulator (HILSIM).



- PIGU : Primary INS/GPS Unit
- SIGU : Secondary INS/GPS Unit
- ATU : Actuator Unit

Fig. 7. HIL test environment

4.2 HIL Test Result

Test scenarios related with the automatic landing include various and more severe conditions than real flight as following:

- Aircraft weight variation
- Center of gravity(C.G)
- Navigation attitude/acceleration accuracy
- Navigation position accuracy
- Air data system accuracy
- Latency of data link
- Accuracy of PLT
- All directional wind/turbulence
- Entry distance(effects on path angle)
- Relative position of landing standby point

Fig. 8 shows automatic landing touchdown dispersion of the HILS testing. The landing accuracy satisfies the landing zone requirement in spite of more severe conditions than flight test i.e., high tail wind condition. The result of landing dispersion has a bias to the right for about 1m. It is the result induced by the effect of anti-torque of the throttle increasing during 1st flare phase. The anti-torque of the propeller increases roll error of the control loop during flare and effects on the final touch down position error. The correction parameters are tuned to recover anti-torque effect by flight test.

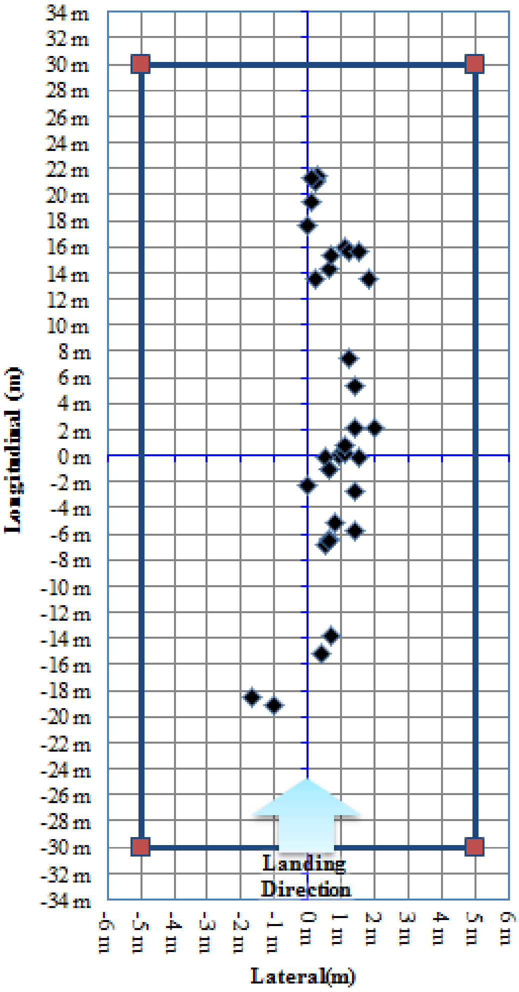


Fig. 8. Touch-down dispersion - HILS

4.3 Flight Test Result

The flight test of the automatic landing contains high risk of landing failures compared to normal flight tests due to short time to recover contingency. In case of steep landing, vertical acceleration at touch down maneuvering is higher than normal landing.

The test plan was set up by six steps to verify the automatic landing performance gradationally.

- Step 1. Basic performance test includes climbing/descending, stall, flap tests to update the dynamic model of the HILS system.
- Step 2. The performance testing and gain tuning of the control law to verify altitude, speed, and attitude control loop.
- Step 3. The offset pass testing to verify the guidance and landing mode management logic without PLT passing through the virtual TDP in the air (Above Ground Level 70m). The test flag was used to replace the source of position data as GPS/INS instead of PLT and to remove the engine stop command and 2nd flare logic. The expected touch down accuracy of guidance is analyzed though this test.
- Step 4. PLT performance test to verify accuracy of PLT and to analyze properties of sensor.
- Step 5. Manual abort test to verify logics of the flight management and PLT integration S/W in condition of the safe approach distance
- Step 6. Auto landing test to verify system’s performance finally. It is also performed from the low glide slope angle to the high slope angle step by step. The first auto landing test was performed to verify touch down accuracy only without 2nd flare.

The flight test for automatic landing had been performed for more than a hundred of times in all-weather conditions. Fig. 9 shows touchdown dispersion from the desired TDP through flight test. In spite of strong wind conditions, UAV landed inside the landing zone perfectly.

Table 4 shows statistics of touch down point errors with average along track error -3.5m, cross track error 0.8m.
Maximum along-track error distance is 25m and cross track error is 4.4m for one time. But it’s a result of initial development phase. During flight test, guidance and control parameters are updated and finally touch-down dispersion reduced less than 18m for along-track, 3m for cross track and touch down shock less than 1.5g.

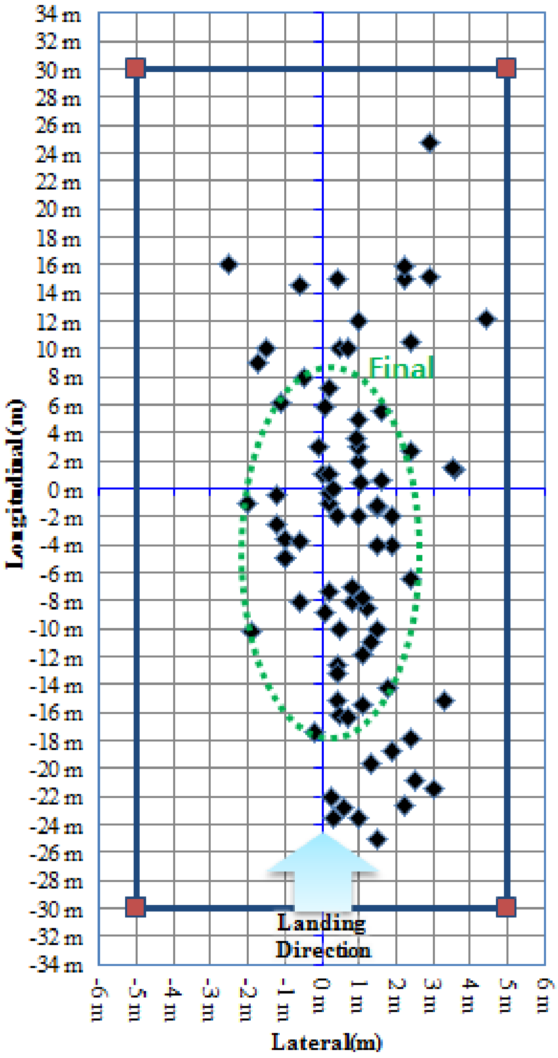


Fig. 9. Touch-down dispersion - Flight test

Table 4 Touchdown dispersion summary

Accuracy	Longitudinal	Lateral
Average	-3.5m	0.8m
Standard Deviation 1σ	11.5m	1.4m
Max	25.0m	4.4m

5 Conclusion

The guidance and control law was designed for a tactical UAV to meet requirements of the automatic landing considering narrow area, steep approach slope and robustness to heavy winds. The two stage flare maneuvering is a good solution for steep glide slope. The 1st-stage flare maneuvering is designed to satisfy the minimum requirement of the touch down acceleration while maintaining the landing accuracy. The 2nd-flare maneuvering reduces vertical speed before touch down and prevent the porpoising.
Through the HIL test and flight test, dispersion of touch-down is verified within 5m cross-track and along-track within 30m. The guidance and control law of the tactical UAV had been met requirements of operation including precise landing accuracy and flight safety.

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