Guidance and Control Techniques of Carrier-Based Aircraft for Automatic Carrier Landing

Zhen Ziyang[1*], *Zhang Zhibing*[2], *Zhang Junhong*[3]

1. College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P. R. China;
2. Shenyang Aircraft Design and Research Institute, Shenyang 110000, P. R. China;
3. Xi′an Aircraft Design and Research Institute, Xi′an 710000, P. R. China

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Abstract: We summarize the guidance and control techniques of automatic carrier landing for carrier-based aircraft. First, we analyze the carrier landing operations of the manned fixed-wing aircraft, unmanned fixed-wing aircraft and helicopters. Second, we look into the navigation and guidance system and the flight control methods for current different aircraft. Finally, we draw several conclusions of the development prospects for aircraft carrier landing, including the precision landing control techniques, precision approach and landing guidance techniques, and adaptive, reconfigurable and intelligent flight control techniques.

Key words: carrier-based aircraft; automatic carrier landing; guidance; flight control

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0 Introduction

The first arrested carrier landing on the aircraft carrier occurred on 26 October, 1922, when Lieutenant Commander Godfrey de Chevalier flew an Aeromarine 39B biplane on the USS Langley[1].

Successfully landing on a moving aircraft carrier in rough seas is quite difficult, because: (1) The translation and rotation of the carrier deck is intensified in inclement weather, and the carrier deck simultaneous oscillatory in six degrees of freedom may cause landing accidents; (2) the limited size of the landing area is so small that it can hardly meet the aircraft need for accurate landing; (3) the airwake behind the carrier due to the carrier′s own presence and motion can seriously impact the glide slope tracking and landing performance.

Aircraft are the key composition of the aircraft carrier battle group (CVBG), including manned aircraft, unmanned aerial vehicles (UAVs), helicopters and so on. Different types of aircraft have different landing methods. With the development of the electronic technology, the carrier landing has evolved into an easier operation for pilots. The automatic carrier landing system (ACLS) has also been developed into a great aid to the pilot of the manned aircraft, and is becoming an essential part of the carrier landing of the unmanned aircraft. Traditional ACLS mainly includes a shipboard guidance system and an airborne flight control system. Data link roll commands are used to intercept and lock onto the landing pattern. The shipboard guidance system establishes the proper glide path, calculates the guidance command and deals with the deck motion compensation, while the airborne flight control system provides flight path tracking control until the aircraft′s touchdown on a carrier. The guidance and control are one of the key techniques of automatic carrier landing. Many kinds of control theories were investigated for ACLS, inclu-

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[*] Corresponding author, E-mail address: zhenziyang@nuaa.edu.cn.

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ding fuzzy logic[2-3] and robust control[4-6]. And the neural network, fuzzy logic, evolutionary algorithm and adaptive control approaches were compared for carrier landing[7].

Deck motion and airwake disturbances are the main conceptual differences between the carrier/ship based aircraft and the land based aircraft. They are the most significant obstacles for safe recovery of aircraft. Deck motion can directly alter the ramp clearance and shift the touchdown point even though the aircraft′s inertial path is precisely controlled. Therefore, prior to touchdown, the aircraft is usually directed to the predicted rather than the actual touchdown point, to reduce aircraft maneuvering and compensate the deck motion. The airwake or turbulence randomly changes displacement of the flight path, velocity and aircraft attitude. Additional ramp input pitch commands may be applied to assist the aircraft through the airwake or burble in the final about 10 s before touchdown. The U. S. Military Standard MIL-F-8785C includes a statistical model of airwake, which is widely used in current simulation studies. Modeling of the deck motion and airwake is indispensible for the carrier take-off, landing or ship recovery[8-11].

The F/A-18 Hornet is a multi-mission fighter/attack aircraft that can be operated from aircraft carriers and fill a variety of roles: Air superiority, fighter escort, suppression of enemy defenses, reconnaissance and forward air control[12-14]. The X-47B UCAS-D was the first UAV in the world to conduct an arrested landing aboard an aircraft carrier. The F-35C Lightning II Joint Strike Fighter is the U. S. Navy′s newest carrier based fighter.

Ref. [15] summarized the research progress in guidance and control of automatic carrier landing of carrier-based aircraft, which is mainly focus on the manned fixed-wing aircraft. Therefore, this paper extends to survey the developments of the guidance and control techniques of different kinds of carrier-based aircraft.

1 Carrier Landing Process of Different Carrier-Based Aircraft

The carrier-based aircraft can be divided into fixed-wing aircraft and helicopters, or be divided into manned aircraft and unmanned aircraft.

1.1 Manned fixed-wing aircraft

Early carrier jets mainly include F7U Cutlass, FJ-2 Fury, FH-1 Banshee, F3H-1 Demon, F9F Panther, EA-6B (electronic warfare), S-3A (anti-submarine/ship), Grumman E-2C (tactical information), C-2 (cargo/personnel transport), S-3A (refueling), F-8 Crusader, A-7 Corsair II, F-14 Tomcat, F/A-18A/B, F-18E/F, Joint Strike Fighter F-35, and so on.

Carrier landing of the manned fixed-wing aircraft has four primary modes of operation.

(1) Mode I: Fully automatic control to touchdown on the carrier deck.

(2) Mode II: Semi automatic approach supplying the pilot with cockpit displays of glide path and tracking deviation data in a similar manner as a Flight Director.

(3) Mode III: Manual carrier-controlled approach (CCA) with the system providing aural cues only (talk down).

(4) Mode IA: Full automation for minimums of 200 ft and one-half mile, similar to Mode I but requiring the pilot to take control.

Generally, there are four arrestment wires for tail-hook engagement, located around the nominal touchdown point and spaced 40 ft apart. The aircraft is required to tack a 3.5° glide slope projected by an optical landing system with an approach speed, and clear the carrier′s ramp by 8.4 ft and touchdown with an impact velocity of about 12.36 ft/s.

The landing sequence of the manned fixed-wing aircraft begins at the marshaling point controlled by the carrier air traffic control center (CATCC). The sequence is divided into two phases: Approach phase (flight from the marshaling point to the radar acquisition window) and descent phase (flight from the radar window to touchdown). Details are given in automatic carrier landing system (ACLS) Category III Certification Manual.

1.2 Unmanned fixed-wing aircraft

The capability of autonomous operation of ship based UAVs in extreme sea conditions would greatly extend the use of UAVs for both military and civilian maritime purposes. The factors that hamper the operations are primarily in the launch and recovery stages of flight. A number of recovery techniques have been developed for the shipboard UAVs, including runway landing, net capture, parachute assisted recovery, cable hook recovery, deep stall and many others.

(1) Conventional runway landing

The runway arrested carrier landing method is an obvious option for the large UAVs landing on a large carrier deck, which refers to the huge experience in manned fixed-wing aircraft. The arresting gears such as a tailhook and arresting wires are necessary on aircraft carriers. High precision of glide slope tracking is required. It is sensitive to waves due to high mass and size of the aircraft carrier. Several large UAVs, such as Predator and X-47B, have been successfully operated from aircraft carriers. This landing method has become the standard for recovering the fixed-wing aircraft aboard an aircraft carrier.

(2) Net recovery

The net recovery is the most widely employed method for recovering the small class of fixed-wing UAVs[16-17]. The deck installations are simple and deck space is little. The UAVs captured by elastic nets require neither the landing gears nor special maneuvers. They also do not need to hold the decent rate very precisely as required for conventional runway landing method. This recovery method has been employed by USN RQ-2 Pioneer UAV, Sea-ALL UAV, Silver Fox UAV and Killer Bee UAV. However, it may not suitable for UAVs with front propeller engine.

(3) Cable hook/Skyhook recovery

The cable hook recovery is used to recover the small to medium-size fixed-wing UAVs. The recovery system stops the UAVs in midair, and the cable hook contacts the recovery boom, slides over it and locks on the arresting wire[18]. It provides a safe recovery even in terrible ocean environment, allowing the choice of approach directions. The skyhook technique has been successfully flight-tested and is effective for small or ultra-small UAVs. It employs a vertical suspended wire, freely suspending on a boom or raised by a kite. The UAV flies directly into the wire, and is locked into the hook by a self-locking hook fixed on a wingtip of the UAV[19]. The small SeaScan UAV and ScanEagle UAV developed by the Insitu Group using the skyhook technique.

(4) Parachute/Parafoil recovery

For the fixed-wing UAVs, a minimum airspeed is required to maintain controllable flight. However, it can be aided or even replaced with a parachute system. Various parachute systems are widely used for ground-based UAV recovery[20-21], including the uncontrollable parachute systems, gliding parachutes, dynamic parachutes, parafoils and parasails. A few of UAVs, such as Skyeye (BAE), Eyeview (IAI Malat), Sentry (S-TEC) and Poisk-1/2 (KhAI), use the parafoil recovery as an optional or sometimes for emergency landing.

Besides, there are other recovery techniques presented recently, including the post stall landing[22], bio-inspired perched landing [23], wind sock recovery, trapeze recovery[24] and so on. However, most of them have not been achieved operational status. These recovery methods have disadvantages and are suitable for a narrow class of UAVs[19].

1.3 Helicopters

Helicopters for U. S. Navy application mainly include Sikorsky MH-53, Lockheed XFV-1, Convair XFY-1, Boeing/Bell V-22. General approach and landing procedures for air-capable ships are summarized in Refs. [25-26]. The shipboard recovery task of V/STOL can be operated by starting on a downwind leg, turning to approach the ship from astern, decelerating to hover, hovering over the deck, and descending to the deck[27]. A view of helicopter recovery profile is given in Ref. [27].

Two important features of the landing area for an air-capable ship are the landing spot and the stabilized glide slope indicator (SGSI). The landing spot is the terminal position for both launch and recovery. SGSI is the primary path reference in the vertical axis during the approach phase. There are four general types of shipboard landings: A visual glide path utilizing SGSI, a standard instrument approach to minimums, an emergency approach, and an offset approach or ordnance line-up approach. Prior to approaching and safely landing on the ship, the pilot in command or automatic landing system needs to ensure the following information: Certification, classification, BRC and speed, weather/altimeter setting, relative wind, status of deck lighting (at night), and other useful information.

2 Guidance and Control Techniques of Carrier Auto-landing

The ACLS system is designed to provide safe and reliable guidance and control of the final approaches and landings for carrier-based aircraft. The basic framework of traditional ACLS is given in Fig. 1. ACLS has limited control authority and needs to cope with carrier deck motion, airwake turbulence, reference glide slope tracking and so on. U. S. Navy specifications in ACLS flight development were used to define design guideline criteria and anticipate possible development problem areas. In these specifications, they mainly concerned the ACLS autopilot flight path response, minimum path errors in turbulence, minimum effects of radar tracking noise, structural mode excitation, digital processor and data transmission delays, control system interaction, and flight safety.

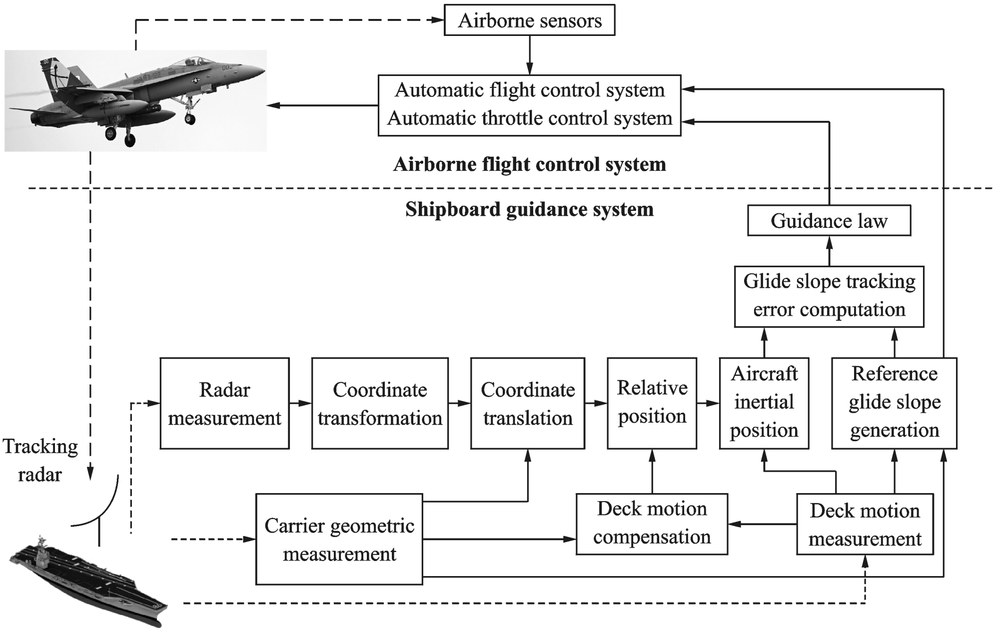

Fig. 1 Basic framework of ACLS

2.1 Navigation and guidance techniques

(1) Precision tracking radar system

The ACLS AN/SPN-42 is an all-weather carrier landing system, which can guide and control the aircraft to land on a moving aircraft carrier during daylight or darkness with minimal interference from adverse sea-state conditions or poor visibility. The major components of the AN/SPN-42 include a precision tracking pulse radar (Ka band), a stable platform, data link monitor, control console, and a high-speed general-purpose computer[28]. The radar tracks the aircraft to determine its actual position in inertial space which removes the effects of the ship′s motion. Altitude and lateral position errors are generated, which are amplified and sent to an α-β filter which estimates the aircraft acceleration, velocity and position errors. These estimates are then passed through a proportional-integral-derivative-double-derivative (PIDDD) controller, to produce corrective pitch and roll commands which are transmitted to the automatic flight control system (AFCS).

Recently, the ACLS AN/SPN-46 is in operational service, which can operate in either true or relative bearing with U. S. Navy gyrocompasses. The AN/SPS-64 radar is a two-dimensional (2D) navigation/surface radar used as a primary search radar on various small combatants and non-combatant ships. The minimum detection range of the AN/SPS-64(V)9 is 20 yards on a radar cross-sectional target of 10 m^2, 3 feet above the surface of the water[29].

Urnes and Hess[30] investigated that the radar tracking system introduces noise into the control loop. Mook[31] and Crassidis[32] presented a flight dynamics based tracking filter to largely reduce the noise. A comprehensive presentation of the ACLS operating procedure can be found in the United States Navy Aircraft Carrier Operations Manual[33], the United States Navy Landing Signal Officers Reference Manual[34] and the United States Navy Training Manuals.

(2) Joint precision approach and landing system

Joint precision approach and landing system (JPALS) is a revolutionary, next generation developed by the Department of Defense (DoD). JPALS includes the sea-based variant, shipboard relative GPS (SRGPS). SRGPS supports all ATC functions including takeoff, departure, marshal holding, approach, landing, bolter and long-range navigation[35].

The shipboard system receives the inertial data and the range and velocity data from the airborne, calculates the wide lane measurements and sends them to airborne system via the data link. The shipboard system also processes the data for deck motion compensation (DMC). The airborne system receives the shipboard GPS and heading data, calculates a position vector from the shipboard GPS antenna to the airborne GPS antenna, and then calculates a tail-hook-to-touchdown point relative position vector. The airborne system also compensates for deck motion, and provides the necessary inputs for the automatic flight control system (AFCS)[36].

Nowadays, vision-based navigation and control strategies have been investigated in the ship landing problems of aircraft[37-38].

2.2 Flight control techniques

The AFCS or autopilot provides the interface between the data link and the aircraft flight control surfaces. In the previous carrier-based aircraft, the AFCS provided switching and signal conditioning, engaged logic, failsafe interlocks and commanded signal limiting. The vertical and lateral position deviations from the reference glide path and track are calculated and input to the flight controllers. The AFCS controls the attitude angles, velocity and path of the aircraft.

Recently, many advanced control methods have been investigated in the carrier landing control problem.

(1) For the manned fixed-wing aircraft: Ref. [39] designed an H_2 preview control system for automatic landing control of F/A-18. Ref. [40] designed three kinds of guidance controller for F/A-18A, namely, PID, Fuzzy-PID, PIDDD controller, and found that PIDDD controller was the most reliable to adapt to airwake and deck motion disturbances. Refs. [41-42] optimized the control parameter for F/A-18 ACLS of via pigeon-inspired optimization and simplified brain storm optimization approach, respectively. Ref. [43] designed an adaptive constrained back-stepping controller for carrier landing. Ref. [44] designed an extended state observer based active disturbance rejection control (ADRC) scheme for F/A-18 ACLS in final approach in the presence of airwake turbulence and deck motion. Carrier approach and recovery precision enabling technologies (MAGIC

CARPET) which are based on the augmented guidance with integrated controls and Head-Up Display symbology for F/A-18E/F/G aircraft, largely improving the landing success rate[45]. An integrated direct lift control strategy is used in the MAGIC CARPET.

(2) For the unmanned fixed-wing aircraft: Ref. [46] designed line-of-sight (LOS)-based guidance laws and linear baseline controller augmented with L1 adaptive controller, which was tested on a full-scale UAV model. Ref. [47] designed an overall guidance, navigation and control system where the adaptive auto-landing algorithm was integrated. Ref. [48] designed linear quadratic optimal controllers for an A/V-8B Harrier like UAV. Refs. [49-51] applied the adaptive back-stepping control methods to the Silver Fox UAV. Refs. [52-58] presented a total energy management control, optimal preview control and model reference adaptive control (MRAC) based ACLS for the Silver Fox UAV, F/A-18 and UH, respectively. Ref. [59] designed an adaptive sliding mode control law and verified it in a coupled 6-DOF nonlinear relative motion model. Ref. [60] studied linear quadratic tracker and model predictive control (MPC) for UAV auto-landing on a moving carrier deck.

(3) For the helicopters: Ref. [61] presented an intelligent reconfigurable control system for autonomous landing of a VTOL UAV on a destroyer helicopter deck. Ref. [62] presented a sequential-loop closure, compensatory pilot control strategy for ship landing of UH-60 rotorcraft. Ref. [63] developed a PID based Yamaha Attitude Control System for ship launch and landing of Yamaha RMAX UH. Ref. [64] proposed a novel back-stepping control system of a rotary wing UAV for launch and recovery from the surveillance boats. Ref. [65] demonstrated the principle of UH ship landing, designed LOS guidance and investigated the classical and modern control methods. Ref. [66] designed a linear MPC scheme for ship landing of helicopter at rough seas, which showed the feasibility of ship landing operations with various constraints.

3 Conclusions

The future techniques of guidance and control for the carrier-based aircraft are concluded in the following:

(1) Precision landing control techniques: Project MAGIC CARPET improved the safety of carrier landings by the combination of flight control enhancements and advanced heads up display (HUD). The flight tests of recent years showed that the touchdown dispersion was reduced more than 50% and the approach workload of pilot was greatly reduced. Actually, practical integration of direct lift control effected through trailing edge flaps and spoilers in the F-14A and associated ACLS was presented very early[67].

(2) Precision approach and landing guidance techniques: The JPALS is an all-weather landing system based on the differential correction of the GPS signal. It is capable of providing a coupled auto-landing capability enabling autonomous landing of aircraft, especially for the unmanned aircraft on aircraft carriers or ships. It is becoming the most mature guidance system of the UAVs in approach and landing.

(3) Adaptive, reconfigurable, and intelligent flight control techniques: U. S. Naval aircraft included the fuzzy logic in the orbit improvement system of the E-6A, the reconfigurable control laws on F-18E/F to deal with stabilator actuator failures, an adaptive neural network compensated for modeling errors and failures on the X-36, and a static neural network with the stability and control parameters for on-line control optimization on the ACTIVE F-15. The use of online parameter identification was used in the VISTA F-16. All above facts show that the adaptive, reconfigurable, and intelligent flight control techniques are indispensible for carrier landings in the complex landing environments.

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Dr. **Zhen Ziyang** received his Ph. D. degree in control theory and control engineering from Nanjing University of Aeronautics and Astronautics (NUAA) in 2010. He joined NUAA in September 2010, where he is currently an associate professor in College of Automation Engineering, NUAA. His research interests are flight control of aircraft, preview control and adaptive control.

Prof. **Zhang Zhibing** is currently a member of Shenyang Aircraft Design and Research Institute. His research interest is flight control of aircraft.

Prof. **Zhang Junhong** is currently a member of Xi′an Aircraft Design and Research Institute. His research interest is flight control of aircraft.

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