A Safety Strategy for High-speed UAV Landing Taxiing Control

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Abstract

In terms of safety for landing taxiing control of high-speed unmanned air vehicles (UAVs), key safety-critical factors were first. A generic taxiing control logic was put forward, incorporating the concerned factors. For further verification, a nonlinear mathematic model was deduced with high accuracy for ground motion simulation, incorporating the characteristics of undercarriages, brake, nose wheel steering and runway condition. Simulations show that the control logic works well and provides sufficient safety assurance in even extreme situations experienced.

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1. Introduction

The recovery stage is a key phase for UAV during the whole flight, and effective control of landing recovery phase is one of the key contents of flight control for UAV. Recovery methods generally include wheeled slippery stop recovery, hindered nets recovery, air salvage recovery and parachute recycling. Comparing with other recovery methods, wheeled landing is more challenging for flight control. The parameter uncertainties of configuration, aerodynamics and runway condition require more considerations for high-speed UAV[1].

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It’s difficult to model the landing gear system accurately, and generally need ground taxiing test calibration. Ground taxiing test is only conducted for low-speed parts because of restriction of nose wheel shimmy and draught device, while the high-speed parameters are assessed through parameter identification and fitting of low-speed parts. Considering the phase transition for air control and taxiing control, all kinds of signal and actuator faults, high speed taxiing security are required to design meticulously [1-5].

The flight control security involves system and hardware configuration and control scheme and onboard software realization, etc. The control scheme is the core, because it is constructed on consideration of the nominal model and modeling error range. The control scheme also needs to endure that the hardware system must be frequency fault, and meet the actual use of the environment.

Taking control strategy for key, according to the study of high-speed unmanned spacecraft taxiing control goal, comprehensive analysis of the influence factors of taxi safety, forming non-straight taxiing control strategy, and through the simulation verified.

2. Objectives of taxiing control

The purpose of ground taxiing control is to maintain the taxiing path of UAV along the runway centre line within allowable lateral deviation limits under possible adverse conditions, such as system failure, wind interference, and adverse runway condition. Based on the taxiing requirements of UAV airworthiness regulations, we propose the design objectives of taxiing control as following [1,8]:

- Lateral deviation of UAV from runway centre line should be less than specific limits, for example, 25 meters;
- Control operation should be moderate to prevent side tumbling;
- Control actuation should be harmonized to assure smooth transient dynamics in transformation.

The above objectives should be achieved under the following adverse situations of system failures, environment effects, and uncertainty:

- Crosswind up to 10m/s;
- Wet or slippery runway;
- Failure conditions of relative airborne systems;
- Loss of brake on one wheel;
- Model uncertainty.

Among the above situations, system failures could be determined through failure frequency and hazard severity analysis of system safety assessment. The following failures are considered in this paper:

- Failures of Weight on Wheel (WOW) sensors, including: failure of WOW signal of single main wheel, failure of WOW signal of both main wheels, failure of WOW signal of all three wheels, unidentified failure of WOW signal of all three wheels, and incorrect WOW signal in air flight;
- Failures of control actuations, including: failure of Nose Wheel Steering (NWS) control, failure of rudder, and failure of brake control;
- Tire burst or lock.

3. Landing taxiing control

3.1. Strategy

High-speed UAVs always have nose wheel steering, differentiate brake and rudder for taxiing lateral deviation control. To achieve the objectives of taxiing control, the controller should use all three effectors above. Ailerons should be engaged to maintain wing level, i.e. preventing side tumbling. In addition, air
speed brake, wheel brake and all possible aerodynamic surfaces should be utilized together to provide decelerating abilities as much as possible for shorter landing taxiing distance.

Both nose wheel steering and differentiate brake could generate effective lateral deviation correction control in low-speed phases. In high-speed taxiing, however, the large lift of UAV decreases wheel pressure on ground, which reduce the static friction of tires significantly. The resulting decrease of nose wheel swerving ability and differentiate brake efficiency might not satisfy the taxiing correction requirements. Meanwhile, the aerodynamic efficiency of rudder deflection increases as taxiing speed gets higher. Therefore, rudder should be used as the primary approach for taxiing lateral deviation correction in high-speed phase of ground taxiing.

To fulfill the objectives proposed above, the following logics proposed based on the flying characteristics of this high-speed UAV are shown at Figure 1:

- After touchdown of single main wheel, the pitch angle is maintained at +4 degrees. Wings level is achieved by aileron deflection. Rudder is used for lateral deviation correction in directional channel. This strategy assures that the UAV could maintain a large pitch angle to avoid the nose wheel touching down before main wheels, even at situation when the WOW sensor provides incorrect signal in air flight;
- After all three wheels touch down, airspeed brake is deflected. Wheel brake is then engaged when ground speed is lower than critical brake speed. Differentiate brake is activated only in emergency situation when blending signal of lateral deviation and ground speed directional angle is larger than boundary limit. The advantage of this approach is using brake system primarily for deceleration, thus eliminate the reduction of braking efficiency when differentiate wheel brake is used frequently for directional control. Meanwhile, the nose wheel steering and rudder deflection could provide sufficient control power for lateral deviation control;
- When indicated airspeed is lower than VC4, fuselage flap is deflected downwards to provide additional pitch-down moment for larger pressure of nose wheel to enhance efficiency of nose wheel steering swerve. Meanwhile, elevator is settled at designated upward deflection angle for larger negative lift to increase pressure of main wheels on ground;
- When ground speed is lower than Vt1, nose wheel steering correction logic is engaged, while rudder deflection correction is still activated. Differentiate brake is used only in emergency, like the control pattern in high speed;
- Control logic of actuator failure is shown in Figure 1 and 2. In high-speed taxiing, if rudder fails, differentiate brake will be used as primary control for lateral deviation correction, while nose wheel steering is utilized for emergency (similar to utilization of differentiate brake in normal mode). If wheel brake fails, then, nose wheel steering is used for emergency. If both rudder and wheel brake fail, nose wheel steering is used for lateral deviation correction. In low-speed taxiing, if nose wheel steering fails, then, differentiate brake is activated for lateral deviation correction.

Among Figure 2 and Figure 3, Vtlim is the critical braking velocity. DrF is rudder failure flag, with 1 for failure and 0 for normal. NWSF is failure flag of nose wheel steering. BRKLF and BRKRF are failure flags of left and right wheel brakes. VC is indicated airspeed, and Vt means ground speed. Yrw is offset lateral deviation distance of UAV from runway centre line in runway coordinate. PSD is ground speed directional angle of UAV in runway coordinate.

3.2. Logic of critical phases switch flags

Control strategy of the above section indicates that there are two critical transformation flags in landing taxiing procedure: touchdown flag of single main wheel and touchdown flag of all three wheels. Touchdown of single main wheel indicates the transformation of flight phase from flare to taxiing. While
flag of all three wheels touching down is activating condition of decelerating devices, such as wheel brake and airspeed brake. Therefore, the determination of single-main-wheel touchdown flag and three-wheel touchdown flag are critical conditions effecting flight safety.

The judge logic for single main wheel touchdown is shown in Figure 4. It can be seen that the single main wheel touchdown flag is judged through WOW signal of main wheel, height about runway and indicated airspeed. This logic assures that the judge of single main wheel touchdown is activated when landing gear is released down and the flight phase is approach, eliminating the possibility of transforming into taxiing phase when UAV is flying in other phases. If WOW sensors of both main wheels fail, the flight control law will use height above runway and indicated airspeed to determine if the aircraft has touched down, thus assuring that the flight logic could still transform into landing taxiing phase. Among the above logic, the indicated airspeed VC1 and VC2 should be determined by simulation with safety constraints. If indicated airspeed fails, equivalent indicated airspeed calculated from ground speed will be used for logic determination.

The judge logic for all three wheel touchdown is shown in Figure 5. This logic also uses indicated airspeed, WOW sensor failure and WOW signal for determination, which is similar to logic of single wheel touchdown determination. Failures of single WOW signal, two WOW signals, and all three WOW signals are considered in this logic. When WOW signal of a wheel is annunciated failed, the flight control law will set WOW signal of this wheel to 0 automatically. This criterion assures the internal consistency of designed control logic. The indicated airspeed threshold values VC2, VC3 and VC4 will be determined through simulation.

Among the above logic, LGH is landing gear release flag. A/L is approach/landing flight phase flag. WLF is WOW signal failure flag of left main wheel. WRF is WOW signal failure flag of right main wheel. WNF is WOW signal failure flag of nose wheel. WL is WOW flag of left main wheel. WR is WOW flag of right main wheel. WN is WOW flag of nose wheel. H is height above runway.

3.3. Structure of controller

Figure 6 shows the structure of ground taxiing controller. In the controller, the Autopilot Command Generator module calculates yaw rate command and roll rate command from lateral position data provided by navigation system. The Inner Controller module tracks control command from Autopilot Command Generator, meanwhile generating aerodynamic surface deflection command to stabilize UAV for good flying qualities. The Control Allocation module transforms equivalent aerodynamic surface commands into real actuator commands and accomplishes control reconfiguration for actuator failure. Initialization of actuator command is utilized for transient suppression in mode transformation.

Controller structure for lateral deviation control is shown in Figure 7. The flight control law calculates yaw rate command from current lateral lateral deviation distance and ground velocity directional angle. The yaw rate command enters inner loop of directional control and further generates control command for nose wheel steering, rudder deflection and differentiate wheel brake. The purpose of incorporating ground velocity directional angle and yaw rate is to increase damp for a better dynamic response of lateral deviation correction.

In the lateral deviation controller, the control allocation of brake is followed:

If $BRK_{\text{dif}} > 0$, then

$$BRKL = BRK_{\text{sym}}, BRKR = BRK_{\text{sym}} - BRK_{\text{dif}}.$$

else

$$BRKL = BRK_{\text{sym}} + BRK_{\text{dif}}, BRKR = BRK_{\text{sym}}.$$
where, $BRK_{sym}$ is the largest brake command allowable under current ground velocity. $BRK_{df}$ is differentiate brake command. $nws_{cmd}$ is nose wheel steering command. $\delta_{r\text{-cmd}}$ is rudder command.

4. Simulation

4.1. Motion modeling

Simulation model of UAV ground taxiing is schematized in Figure 8. The Gravity module is used to calculate UAV gravity. Environment and Flight Control Parameters module calculates atmosphere data, wind data, and aerodynamic data like angle of attack, angle of sideslip, indicated airspeed etc. The Aerodynamic Module calculates aerodynamic forces and moments based on control surface deflection and air data. The Ground Motion Model calculates reaction force of runway on UAV. The Mass Propulsion module is used to calculate mass and inertial moment data. The Sensor Model is used to simulate dynamics of flight control sensors. The Navigation Parameters Module calculates navigation and control parameters like descent angle and ground velocity directional angle based on flight parameters. This module also provides some system failure signals.

The simulation model of reaction force between runway and UAV is shown in Figure 9 [1,2,6,7,8]. Input of this model includes velocity of UAV center of mass, height, attitude angle, angle rate, brake command and nose wheel steering command. Output of this model is reaction force and moment on UAV in body frame. The Runway module incorporates runway condition data like dry or wet runway surface. The Tire module calculates reaction force and moment on UAV in body frame from longitudinal and lateral friction coefficients based on strut compression, runway data and nose wheel steering command.

4.2. Simulation results

Flight simulation of demo UAV with the unpowered configuration is performed for validation of proposed control strategy of ground taxiing. Tail protection angle of this UAV is 11 degrees. Only final phrase of approach and landing and ground taxiing are simulated for validation. The unpowered UAV is initially dropped at 60 meters above runway, with an lateral deviation of 30 meters from runway centerline. The descent angle command is set -1.3 degrees for approaching. After touchdown, when vehicle motion is stable, the controller transforms into ground taxiing mode.

Simulation results of nominal configuration are shown in Figure 10. It can be seen that, the transients between modes are moderate. The lateral controller adjusts bank angle for lateral deviation correction in flight phase, while rudder is used to eliminate angle of sideslip for coordinate turn. The longitudinal controller maintains descent angle at approximate -1.3 degrees, which leads to a descent rate of 2m/s when touching down. Angle of attack and pitch angle are both appropriate when touching down. After single wheel touches down, the controller transforms into ground taxiing mode. Rudder is used for lateral deviation correction in high speed condition. In low speed condition, nose wheel steering is adopted for lateral deviation correction. This control strategy corrects the lateral deviation well, with the lateral deviation controlled around 0 meters.

In Figure 10, $BRKL$ is the left wheel brake command. $BRKR$ is the right wheel brake command. WOW1M is the single main wheel touchdown flag. WOW2M is the three wheels touchdown flag. SWNWS is nose wheel steering activation flag. BRKDIF is differentiate brake activation flag.

Simulation results of WOW sensor failure conditions are shown in Figure 11. Since there are too many combinations of WOW sensor failure, this paper chooses the following failure conditions for typical failure of WOW sensor failure:
A. WOW sensor failure of single main wheel;
B. WOW sensor failures of both main wheels;
C. WOW sensor failures of all three wheels;
D. WOW sensor of a main wheel is set REAL in the air, and is not identified;
E. WOW sensors of all three wheels are set REAL in the air, and are not identified;
F. WOW sensors of all three wheels are set REAL in the air, and are not identified; left crosswind of 10 m/s.

It can be seen from the time history response that, the UAV lands safely under all six failure conditions above. In cases B and C, time delay of touchdown judgment causes the vehicle still use in-flight correction mode after touching down, which leads to increase of lateral deviation initially. Then, the controller transforms into ground taxiing mode by indicated airspeed and WOW signal, and starts lateral deviation correction. Cases D, E and F are most severe ones. In these three cases, the vehicle is judged touchdown in air flight phase. The controller manipulates pitch angle for longitudinal control, adjusts aileron to maintain wings level, and uses rudder for lateral deviation correction. The results indicate that, when UAV touches down, the descent rate is 2 m/s, pitch angle is 4.5 degrees, and angle of attack is 6.3 degrees. All parameters concerned fulfills the proposed requirement.

Simulation results of aerodynamic surface actuator failure conditions are shown in Figure 12. This paper chooses the following typical failure conditions for validation:
A. Rudder failure;
B. Nose wheel steering failure;
C. Left wheel brake failure, loss of hydraulic pressure;
D. Combination failures of rudder and nose wheel steering;
E. Combination failures of rudder and single wheel brake;
F. Left tire bursts;
G. Left wheel locks and tire bursts.

Left crosswind of 10m/s are all engaged in above cases. Rudder failure only occurs after touchdown, and settles to neutral position automatically after failure. To simulate burst of left wheel tire, longitudinal friction coefficient of left wheel is reduced 30 percent for normal magnitude, and left gear column is shorted accordingly. To simulate lock of left wheel, the friction coefficient of left tire is increased to twice of maximum nominal magnitude.

The simulation results indicate that, the UAV could accomplish landing safely in all seven failure conditions above. In the most severe case G, the maximum lateral deviation reaches -10 meters, meanwhile, there exists bank angle in taxiing due to tire burst.

Simulation results of adverse runway condition[8] and wind are shown in Figure 13. The following three situations are examined:
A. Wet runway, with left crosswind of 10m/s;
B. Tailwind, wind speed 10m/s;
C. Headwind, wind speed 10m/s;

The time history of dynamic response indicates that, angle of attack, pitch angle and descent rate are all insensitive to constant wind due to relatively high touching down speed. The UAV could accomplish landing safely in all three adverse conditions above.

5. Conclusions

The key factors affecting security are identified for high-speed unmanned aerial vehicle landing taxiing. The control method and logic for taxiing are proposed. The nonlinear mathematic model of UAV taxiing is deduced, and a novel integrated taxiing control simulation model with high accuracy for ground
motion model is presented. The control targets and key security factors are validated. The results indicate that the control method and logic are valid, it’s safe even in extreme situation.

References


Appendix A. Control logic and simulation result

Fig. 1. Landing taxiing control logic

Fig. 2. Differential brake start logic
Three wheel touch down
&&
Vt<Vtlim

YES
NWSF=1

(DrF==1)&&
(BRKLF==1)
&&
(BRKRF==1)

YES

YES

Yrw>0

0.3Yrw
+PSD>3

YES

0.3Yrw
+PSD<-3

YES

Start NWS steering

Fig. 3. NWS steering start logic

LGH==1
&&
fmpase==A/L

YES

WLF==0
&&
WRF==0

NO

WLF==1

YES

WRF==1

YES

NO

H<15m
&&
VC<VC2

YES

H<15m
&&
(WL==1)
&&
WR==1

YES

H<15m
&&
VC<VC1

YES

WR==1

YES

WL==1

YES

Single main wheel touch down

Fig. 4. Single main wheel touch down flag judgement
Fig. 5. Three wheel touch down flag judgement

Fig. 6. Ground taxiing controller

Fig. 7. Structure of lateral deviation combined control
Fig. 8. Simulation structure of ground taxiing

Fig. 9. Structure of ground motion model
Fig. 10. Simulation result of normal taxiing
Fig. 11. Simulation result for wheel load failures

Fig. 12. Simulation result for actuator failures
Fig. 13. Simulation result for runway conditions and constant winds