Automatic Take-Off and Landing Control for Small UAV's

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Abstract

This paper presents an overview of the design of a fully autonomous FCS (Flight Control system) developed for the small UAV's that are part of the BAE SYSTEMS UAV Experimentation System (UES). The UES has been developed to provide flight demonstrations of key enabling technologies for future autonomous systems [1]. A complete FCS, GCS (Ground Control Station), navigation system and HIL (Hardware In Loop) simulator were produced in a 7 month rapid development program to provide a system capable of flying small UAV's from 300m unsealed runways under full autonomous control.

A top level description of the FCS is provided together with simulation results for short field landings and takeoffs in the presence of crosswinds and gusts.

1 Introduction

The UES (UAV Experimentation System) is comprised of multiple small UAV's and ground station that have been developed to provide a flexible system for demonstration of technologies such as Decentralised Data Fusion (DDF) and SLAM (Simultaneous Localisation And Mapping) [1]. The FCS design presented in this paper has been developed for the Kingfisher platform shown in Figure 1.

Figure 1: UAV Experimentation System – Kingfisher UAV during flight test

The Kingfisher vehicle uses the fuselage and powerplant from the Brumby Mk3 delta wing configuration vehicle used in the ANSER project [1] combined with a conventional wing and tail to provide increased payload capacity. It is a precursor to development of a larger platform with increased payload and endurance.

A FCS had previously been developed for the ANSER project flight vehicles to control speed, altitude and position sufficiently accurately to enable low altitude (<150m AGL) autonomous flight with multiple flight vehicle over a small area of 1 sq km. Future experiments required that flights be undertaken beyond visual range, in a wider range of wind conditions with larger payloads and without reliance on skilled pilots.

A new FCS, GCS (Ground Control station) and HIL (Hardware In Loop) simulator were produced over a period of 7 months in a rapid development program that included flight testing and drew from experience gained during the ANSER project [1]. The work presented in this paper is a follow-on task that will implement and trial the FCS in the Kingfisher vehicle with a fully autonomous flight including automatic takeoff and landing. The Kingfisher vehicle specifications are listed below.

Figure 2: Kingfisher specifications

Wing span	4131 mm
Length	3732 mm
Height	980 mm
Mean aerodynamic chord	670 mm
Wing area	2.667 m^2
Wing aspect ratio	6.00
Wheelbase (long)	1176 mm
Wheelbase (lat)	647 mm
Aerofoil wing	NACA 4415 (mod)
Aerofoil horizontal stabiliser	NACA 0012
Maximum take off mass	60 kg
Minimum flying mass	50 kg
Maximum fuel mass	3.9 kg
Maximum payload mass	10 kg

Kingfisher specifications cont'd

Stall speed clean	34 KEAS
Stall speed flaps	30 KEAS (inner wing flaps only)
Approach speed	45 KEAS (inner wing flaps only)
Cruise speed (approx)	55 KEAS
Velocity never exceed	85 KEAS
Endurance	45 min

2 Flight Control System Overview

Figure 2 shows the physical architecture for the Flight Control System (FCS)

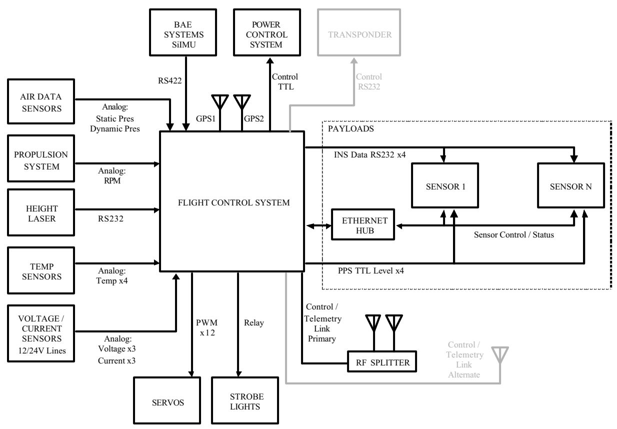

Figure 3: FCS Architecture

A prototype enclosure for the FCS is shown below in Figure 3 with the front of the BAE SYSTEMS Silicon IMU and the roll tilt sensor used for INS alignment clearly visible on the forward end of the enclosure.

Figure 4: Prototype FCS Enclosure

The FCS has been designed to control up to 12 individual PWM servo channels which enables implementation on a wide variety of vehicle configuration. On the Kingfisher vehicle, the actuators driven are:

- Port outer Aileron
- Port inner Aileron
- Port Flap
- Starboard Flap
- Starboard Inner Aileron
- Starboard Outer Aileron
- Port Elevator
- Starboard Elevator
- Port Rudder
- Starboard Rudder
- Throttle
- Nosewheel Steering

The 6 wing trailing edge segments allow spanwise control of wing camber to be used to provide more precise control over lift, drag and control characteristics. Other advantages to the use of multiple surfaces include the ability to use COTS servos from the RC hobby market and robustness to single servo failure. On the Kingfisher vehicle no wheel brakes are required as current operations on grass runways provide sufficient retardation.

FCS processing has been split into low level and high level functions. Low level functions are performed on a Stratix processor which combines a tradition microprocessor and programmable gate array. This provides high integrity control of communications and airframe stabilisation and provides a system that can rapidly recover from in-flight resets. High level functions including guidance, navigation, datalogging and payload control are performed on a 700 MHz PC104 P3 processor running a real time Linux operating system.

2.1 Navigation

The navigation system fuses data from the following sensors using a strapdown inertial navigation system combined with extended Kalman filter for in flight alignment.

- BAE SYSTEMS three axis silicon solid-state inertial measurement unit
- Dual DGPS receivers
- Laser Altimeter
- Dual Clinometers

The system provides poise, position and velocity information with sufficient accuracy to support autonomous takeoffs and landings from a 300m runway after calibration.

2.2 Guidance

The guidance system controls the trajectory of the vehicle by issuing pitch rate, roll rate, lateral acceleration, yaw rate and speed commands to the low level control loops. The guidance system controls the vehicle through all autonomous states from commencement of takeoff to completion of rollout.

2.3 Low Level Control

The low level control system controls vehicle body rates and lateral acceleration using aerodynamic controls in the air and nosewheel steering on the ground with airspeed controlled using a basic autothrottle system. The low level control laws utilise the following measurements:

- differential pressure
- static pressure
- weight on wheels status
- angular rates
- axial accelerations

Full manual reversion is available at all times.

3 Simulation Model Development

A full 6DoF physics model of the flight vehicle was developed using Matlab Simulink to support control algorithm design and testing. Initial algorithm development for the low level control laws was performed using linear models for each control axis. Once the controller for each axis had been developed, they were integrated and tested on the full 6DoF model.

The 6DoF physics model was combined with models of all onboard systems including navigation, guidance and low level control to generate a model capable of simulating a complete autonomous mission from alignment of the navigation system to completion of rollout.

A real time version of the physics model complete with sensor models was also implemented on a high speed PC capable of synthesizing all of the Digital and Analogue inputs to the FCS. This HIL (Hardware In Loop) simulation system enabled autonomous missions to be flown with the FCS, GCS and operator tested in real time, significantly reducing development risk.

3.1 Flight Vehicle Characterisation

Both time and cost constraints prevented the use of wind tunnel testing so linear models for each control axis were tuned and validated using test data from remote pilot operation. A preliminary set of aerodynamic derivatives were obtained firstly using standard datasheet methods [3] and the predicted response due to elevator, rudder, aileron and throttle inputs were compared to measured values. The dominant derivatives were adjusted manually first to obtain a match with numerical optimisation used for final refinement.

The following figures show typical matches between predicted and simulated response due to large amplitude inputs with the simulated response indicated by the dotted trace. The wind was gusting above 20 knots at the time of the test which was performed at 100m AGL so significant gust activity is evident in the measured response, but sufficient control response was achieved to characterise the response about each control axis.

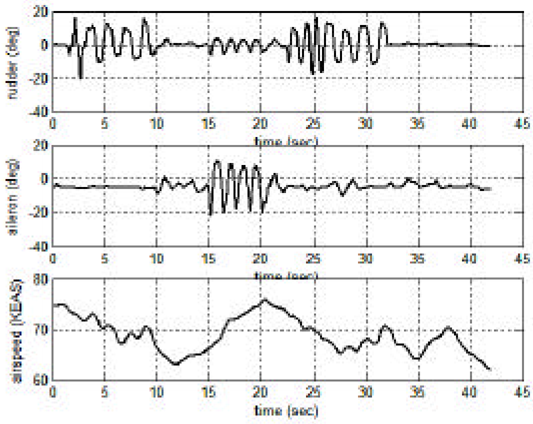

Figure 5: Yaw control inputs

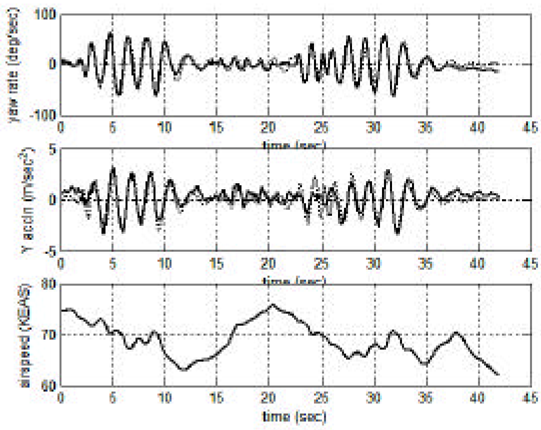

Figure 6: Comparison of measured and predicted yaw response

Lateral acceleration was harder to match than other inertial outputs due to the nonlinear Cy_{beta} characteristics. A small Lateral acceleration offset was also present which can be explained by the yawing moment created by the drag of the pitot-static assembly on the starboard wingtip.

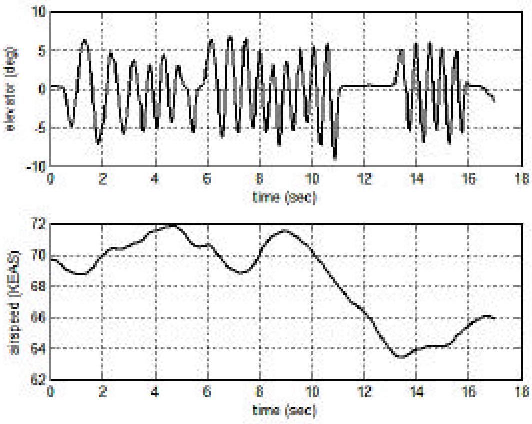

Figure 7: Pitch control input

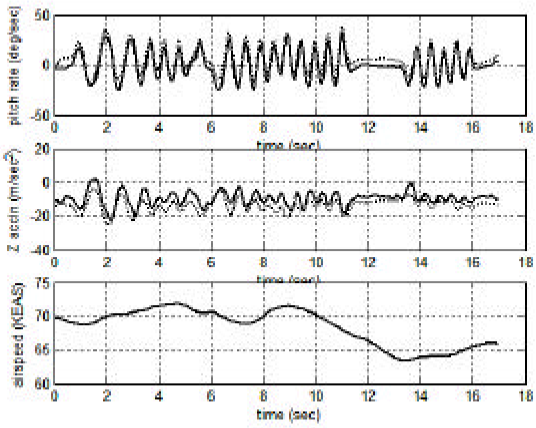

Figure 8: Comparison of measured and predicted pitch response

A steady state trim difference between the simulated and measured longitudinal response was evident, but past experience has indicated that provided magnitude and phase characteristics are matched and sufficient elevator is available to trim through the speed range, integrator terms in the FCS compensate for trim differences.

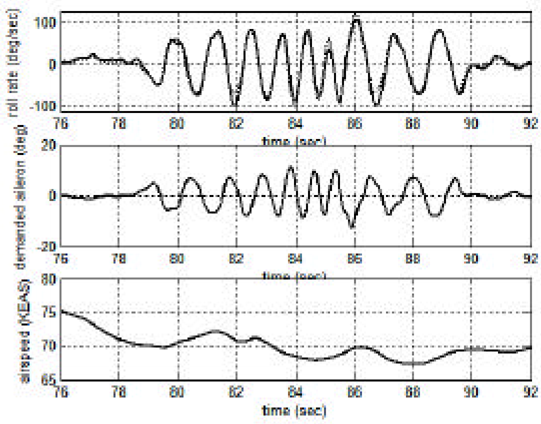

Figure 9: Comparison of measured and predicted roll response

It should be noted that the purpose of this characterisation was to obtain a model that was sufficiently accurate in gain and phase characteristics to support flight control algorithm tuning, rather than to identify specific aerodynamic characteristics. For this reason, angle of attack, angle of sideslip and achieved control surface deflections were not required, the only measurements being available being angular rates, axial accelerations, differential and static pressure. Trim differences between the model and test data were not of concern because the FCS algorithms are inherently self trimming and flight under manual control had already confirmed adequate control authority across the flight envelope.

3.2 Ground Dynamics

The 6DoF model was required to model the interaction between the flight vehicle and runway to a sufficient fidelity to enable development of ground steering laws and to determine preliminary crosswind limits. Ground dynamics were incorporated into the flight dynamics model by addition of a process which calculated forces and moments acting on the air vehicle due to interaction between the wheels and runway surface. The top level block diagram of the process used to calculate ground forces and moments is shown in the following figure.

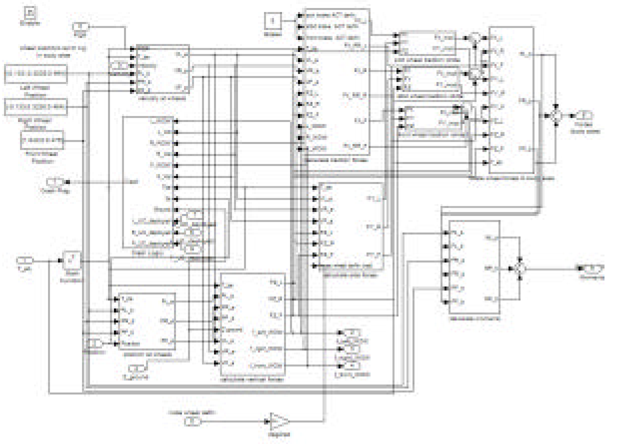

Figure 10: Calculation of ground forces and moments

The calculation of ground forces and moments was split into the following processes:

- Calculation of velocity at each wheel
- Calculation of position at each wheel
- Calculation of traction forces at each wheel
- Calculation of side forces at each wheel
- Calculation of vertical forces at each wheel
- Apply traction circle limit to traction and side forces for each wheel
- Rotate wheel forces to body axes
- Calculate moments in body axes

The interaction between aerodynamic and ground forces and the coupling with control laws is a complex phenomena. Experience has shown tyre sideforce derivatives and rigid body mode frequencies and damping to be the primary factors affecting the ground handling.

3.2.1 Tyre sideforce vs slip angle and normal force

Generic properties were taken from [2] with modification for operation from a grass surface and for the small tyre size used by the Kingfisher air vehicle. It is important that the balance between front and rear wheel properties is modelled to provide correct understeer/oversteer characteristics as this has a large effect on the stability of the ground steering laws

3.2.2 Frequency and damping of rigid body modes

This is determined primarily by the undercarriage compliance, damping, stiction and tyre compliance. The compliance values were measured whereas damping values were based on initial estimates that were adjusted to match observed cycles to half amplitude cycles to half amplitude.

3.3 Ground Effect

Remote pilot operation of the Kingfisher vehicle did not reveal any noticeable pitch change due to ground effect. Pilot comments and logged data did indicate that the lift increase and drag reduction in ground effect was noticeable and had a beneficial effect in reducing vertical speed at touchdown and requiring less pitch attitude during rotation.

Lift and drag increments due to ground effect were incorporated into the simulation, but the effects were found to be small with a slight (5m) extension in touchdown point being the largest effect.

4 Control Law Description

4.1 Low Level Control

Low level control is divided up into the following functions

- Roll Rate Control – achieves a demanded roll rate by issuing aileron deflection demands
- Lateral Acceleration Control – achieves a demanded lateral acceleration by issuing rudder deflection demands
- Pitch Rate Control – achieves a demanded pitch rate by issuing elevator deflection demands
- Speed Control – achieves a demanded speed by issuing throttle demands
- Yaw Rate Control (ground steering) – achieves a demanded yaw rate by issuing rudder and nosewheel steering demands

Classical loop shaping methods are used with combinations of first and second order filters used to pre-shape input demands and achieve the required sensitivity and complementary sensitivity functions.

Transition between in-air and on-ground modes is determined using information from a weight on wheel strain sensor in the main undercarriage.

4.2 Guidance

Automatic takeoff and landing requires accurate control over the flight vehicle trajectory in the presence of wind and gusts. The simple waypoint guidance used during the ANSER project was not sufficiently robust against the effects of wind and did not control height accurately enough to support an autoland function.

A new guidance algorithm was developed that uses the perpendicular distance and velocity from the demanded flight path to calculate a demanded manoeuvre acceleration. The current vehicle speed and orientation is then used to convert this acceleration vector to a demanded roll and pitch rate. This provides a guidance system that is robust to turbulence and crosswind effects and provides tight control of trajectory to sub meter accuracy during straight and level flight and to better than 5 metres during turns.

The trajectory is defined by straight lines between waypoints with constant radius turns at each waypoint. This makes the guidance system completely waypoint driven with waypoints used to define the takeoff run, scenario. circuit, approach and landing positions. Each waypoint is defined in a local North east Down (NED) coordinate system and has the following attributes

- North Position relative to local origin
- East Position relative to local origin
- Down Position relative to local origin
- Demanded Equivalent Airspeed
- Turn Radius

5 Automatic Takeoff and Landing

5.1 Automatic Takeoff

The runway alignment during automatic takeoff is defined by a straight line joining two waypoints which are surveyed using navigation system data gathered during taxi tests. In practice the horizontal repeatability of the navigation solution is better than +-2m. The following figure shows North East position results from a navigation test. Such testing enables the calibration of the navigation sensors and runway survey to be performed simultaneously.

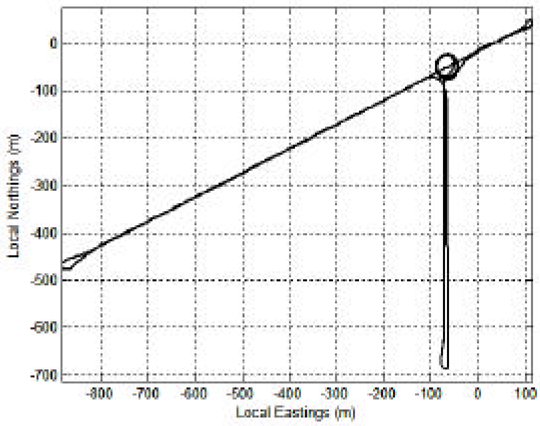

Figure 11: Navigation output from runway ground tests

After initialisation, navigation system alignment and engine startup, the vehicle is taxied manually to the holding point before the Ground Control Station (GCS) operator manually initiates takeoff. Safety interlocks in the guidance prevent initiation of takeoff if the position or vehicle heading differ significantly from the holding point.

The guidance system commands full throttle and issues yaw rate commands to the low level controller to maintain vehicle alignment with the runway centreline. At a preset airspeed, a rotation manoeuvre is commenced by applying a positive pitch rate to maintain and hold a constant pitch angle. Under normal takeoff conditions the vehicle will be airborne before the full pitch angle is achieved. A reliable liftoff indication is provided using a combination of weight on wheels, airspeed and climb rate.

After detection of an airborne flight condition, the guidance system transitions automatically to a climbout state where the pitch angle is maintained by issuing pitch rate commands, horizontal track is maintained by issuing roll rate commands to the low level controller and full throttle is maintained. Climbout is completed when the vehicle achieves a specified altitude. At this point, the guidance system transitions to normal control of height, horizontal track and airspeed.

The following figures show the track error during takeoff with a 10 knot crosswind component from the port side combined with moderate gusts. Full throttle was applied at 130 seconds which is not evident in the speed response due to the IAS display floor of 20 knots with wheels off occurring at 137 seconds. The short takeoff run is characteristic of the Kingfisher UAV due to a good power/weight ratio and low stall speed.

The small step in track error at 137.2 seconds is caused by the guidance switching over to the climbout waypoints which effectively offset the reference track by a metre. A maximum rudder deflection of 20 degrees was required to hold track which indicates that the Kingfisher vehicle is close to its crosswind operating limit. This result agrees with observations made during remote pilot operations.

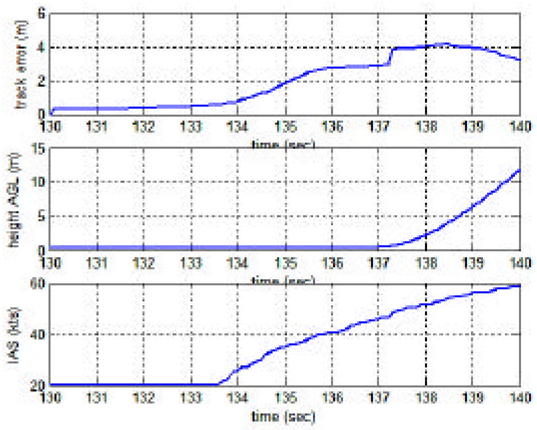

Figure 12: crosswind takeoff - tracking performance

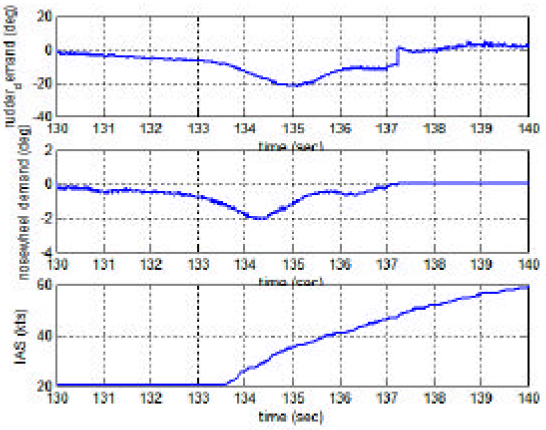

Figure 13: crosswind takeoff – control deflections

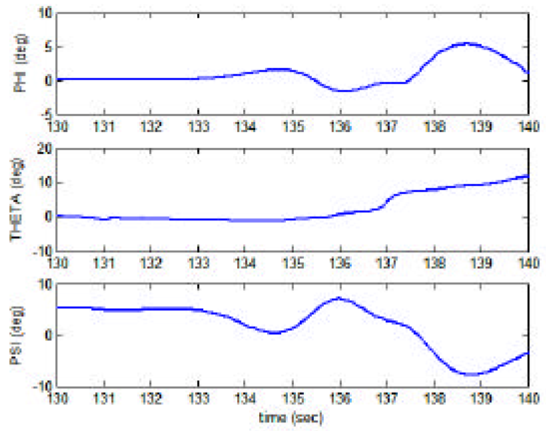

Figure 14: crosswind takeoff – Euler angles

High forward path gains were required for effective yaw control during crosswind operation as feedback gains could not be increased further without feeding excessive noise to the actuators.

5.2 Automatic Landing

The automatic landing is initiated from a circuit after passing a waypoint defining where the vehicle exits circuit and commences the landing approach. This exit occurs automatically but can be inhibited by the operator if it is necessary to repeat the circuit for any reason. The approach trajectory is defined by a straight line which intersects two waypoints and the vehicle is flown along the approach path at the specified approach speed which for the Kingfisher vehicle is nominally a 6 degree glideslope flown at 45 to 50 knots. The operator can abort the approach at any time which causes the vehicle to climb and rejoin the circuit.

When the vehicle passes the end of approach waypoint, the guidance system automatically transitions to the landing phase. During this phase of flight both vertical and cross track errors are monitored and the landing is aborted and circuit rejoined if the flight vehicle passes outside what is effectively a rectangular corridoor about the landing trajectory. The landing trajectory is defined by a straight line linking two waypoints, with the end waypoint located at the touchdown point and the vehicle is flown along the trajectory at the specified landing speed. During this phase of flight, the laser altimeter is used to correct height errors in the navigation solution which enables initiation of the flare manoeuve at the correct height and minimises along track dispersion of the touchdown point.

The flare maoeuvre is commenced when the vehicle altitude passes an altitude threshold that is set adaptively using estimated navigation errors and descent rate information. Initiation of the flare manoeuvre at the correct height is important because if the height is too low, the descent rate on touchdown will be excessive risking damage to the undercarriage. Conversely an excessive flare height results in an extended touchdown point and also can result in excessive speed loss during the flare as the throttle is closed during this period.

During the flare manoeuvre, the descent rate is reduced and held and the crosswind induced crab angle is reduced with the rudder to lower undercarriage sideloads and yaw transients on touchdown. The autothrottle system is disengaged and the throttle retarded to idle at the start of the flare manoeuvre.

The following figures show simulation results for the Kingfisher vehicle performing an autolanding with a 10 knot crosswind and moderate gusts. Approach is commenced at 300 seconds into the flight with transition into landing at 338 seconds and touchdown at 362 seconds. An approach speed of 50 knots was used with a glide slope of 6 degrees which is the steepest approach that allows effective speed control at the selected flap setting of 10 degrees during the landing phase.

Flap deployment resulted in a transient 2.5 m height rise above the demanded glideslope and a nose down pitch change that is evident at 340 seconds and corrected by 348 seconds after the FCS had retrimmed.

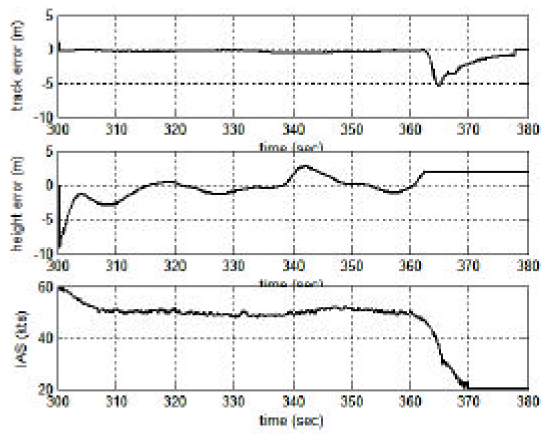

Figure 15: crosswind landing – position errors

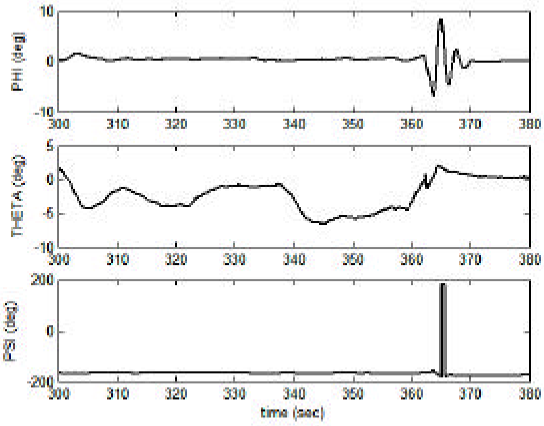

Figure 16: crosswind landing – Euler angles

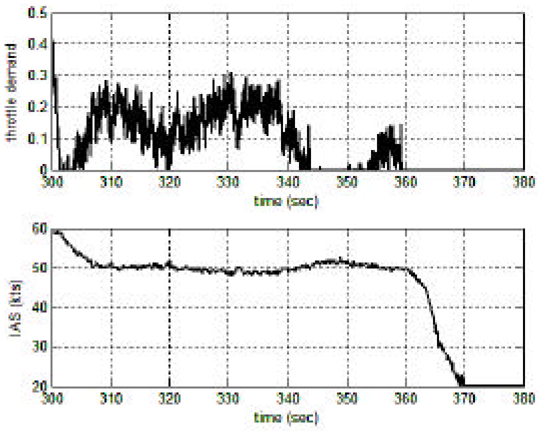

Figure 17: crosswind landing – autothrottle response

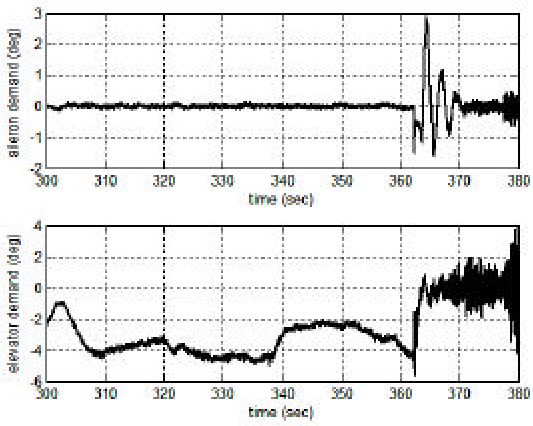

Figure 18: crosswind landing – lateral control

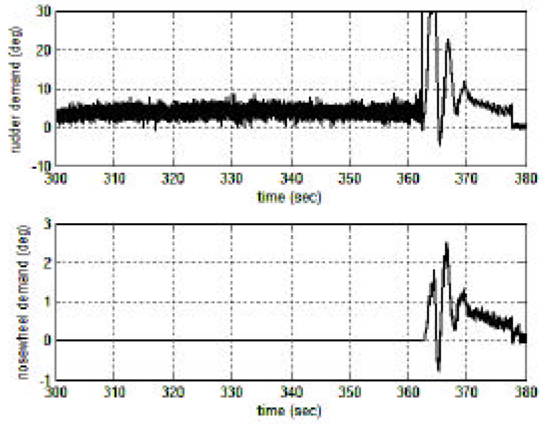

Figure 19: crosswind landing – ground steering control

This combination of crosswind, gusts and landing speed resulted in a 5 metre dispersion from the runway centreline and a saturation of rudder demand at the 30 degree deflection limit. The landing is more sensitive than the takeoff to crosswinds for the following reasons:

- Reduced control authority due to lack of propellor slipstream.
- The inherent stability of the tricycle undercarriage geometry is reduced by the forward weight transfer during rollout
- Uncorrected crab angles at touchdown cause large lateral transient weight transfer immediately after touchdown which results in coupled roll and yaw at a frequency determined by undercarriage compliance. This frequency is low for the Kingfisher configuration due to the relatively narrow track undercarriage and undercarriage attachment.

Careful tuning is required to ensure that the rolling mode and yaw controller natural frequencies do not couple. Evidence of this coupling is evident in the simulation results for the 10 knot crosswind case, but verification of the ground dynamics against test data is required before further tuning is performed to increase crosswind operating limits.

6 Conclusions

The paper presented an overview of a navigation and flight control system designed for fully autonomous operation of small UAV's including automatic takeoff and landing. Simulation results are presented which demonstrate effective control of trajectory and touchdown point in the presence of crosswinds and gusts. A potential coupling mode between autopilot and ground dynamics is identified and discussed.

References

[1] J.H.Suttcliffe, and S.Sukarrieh, *Decentralised Tracking and SLAM Applied to UAV Sensing and Operations*, 10th Australian International Aerospace Congress 2003, Proc. 112.

[2] R.F.Smiley & W.B.Horne, *Mechanical Properties of Pneumatic Tires with Special Reference to Modern Aircraft Tires*, NASA TR R64

[3] J.Roskam, *Airplane Design Part VI*, Roskam Aviation and Engineering Corporation, 1987