AN AUTONOMOUS CONTROL TECHNIQUE FOR LAUNCHING SHIP BASED UNMANNED AIR VEHICLES (UAVS) IN EXTREME CONDITIONS

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Abstract

This paper presents a solution to the autonomous control problem for launching unmanned air vehicles from maritime platforms in extreme conditions. A controller is developed utilising both linear robust modern control theory ($\mathcal{H}_\infty$ methods) and a new approach involving trajectory optimisation and system identification. The resulting controller is found to allow the aircraft to fly to its physical limits. This controller has been found to have very good robustness properties through extensive simulation.

1 Introduction

The ability to launch ship based Unmanned Air Vehicles (UAVs) in extreme sea conditions would greatly extend the usefulness of these aircraft for both military and civilian maritime purposes. Currently the majority of ship based UAVs are either VTOL aircraft or fixed wing aircraft remotely launched under limited conditions. The advantages of fixed wing aircraft over VTOL aircraft in terms of flight speed, range and endurance are well known, and can be of great benefit to various missions. Thus there exists a need for fixed wing UAV operation off maritime platforms.

Remote launch procedures involving an external human pilot are generally very labour intensive and prone to both technical and human factor complications which can result in the complete loss of the aircraft and full mission failure. This situation is exacerbated by extreme environmental conditions (both oceanic and atmospheric). Autonomous control of the UAV during the launch procedure has been identified as a key technological requirement for ship based fixed wing UAV operations.

The major problem identified when launching a small UAV from a ship deck results when a large tailwind is present. This large tailwind reduces the aircraft airspeed during the launch process, resulting in both loss of controllability and aircraft stall, either of which can be catastrophic during launch. As opposed to launch from conventional runways, where multidirectional launch capability is generally present, a relatively small ship deck presents limited launch directions and it is undesirable to manoeuvre the ship to allow a feasible launch direction. Thus, launch in these tailwind conditions becomes necessary in some situations.

Other problems identified include large amounts of turbulence through the ship airwake presenting large disturbances to the aircraft which a controller (or human pilot) must be able to cope with.

This paper presents a control and guidance strategy that allows autonomous launch of a fixed wing UAV under a large set of environmental conditions, including conditions exhibiting the turbulence and tailwind problems. It is found that the limiting conditions for launch when implementing this controller are physical limits that are set by the aircraft dynamics and not those set by the controller. Thus, the controller allows aircraft launch through the entire physically possible aircraft launch envelope.

This controller is developed using a combination of both modern linear robust control techniques ($\mathcal{H}_\infty$) and a newly proposed control method. The robust linear controller controls the aircraft through the majority of the launch phase, guiding the aircraft along a nominal trajectory whilst rejecting external disturbances in the form of turbulence from the ship airwake. The controller has been designed using a variation of the $\mathcal{H}_\infty$ mixed sensitivity approach.

Control for high tailwind launches is provided initially by a *Trajectory Optimisation with Inverse System Identification (TOISI)* controller. This controller guides the aircraft through a minimum altitude loss trajectory, whilst maintaining a nominated climb angle. Once a safe climb regime has been obtained, the controller switches to the linear robust controller, which guides the aircraft to a safe altitude where a mission controller may operate.

This technique has been tested comprehensively in nonlinear simulations of the aircraft and has been found to follow the physically optimal launch trajectory in the presence of both uncertainty in the simulation models and external disturbances due to turbulence.

2 Dynamic Models.

The aircraft used for development of the controller is based upon the University of Sydney UAV Ariel [9]. This aircraft is a conventional fixed wing UAV with four main control inputs, throttle, elevators, ailerons and twin rudders located on the twin vertical tails. The simulation model has been slightly modified to give a slight increase in aerodynamic performance around the high angle of attack region. The modified model includes hypothetical aircraft stall and post-stall effects, nonlinear actuator effects (including rate and positional saturation) and sensor limitations.

The ship model is based upon seakeeping theory [10] in conjunction with measured data [6] and some results of simulations based upon a generic frigate type vessel. The simulation allows prerecorded (or artificially generated) motion data to be used, or simulates generic ship motion using a six degree of freedom simple harmonic motion model. The model takes account of the ship heading with respect to wave heading, sea state, ship speed and basic ship characteristics (such as length). The ship model is that of a generic frigate, typical of the Australian designed ANZAC Frigate or the Oliver Hazard Perry Class FFG's in service with the Australian Navy.

The launcher model uses linear dynamics to accelerate the aircraft while constraining aircraft rotation in all dimensions and motion in the ramp normal directions. This simulates an attachment between the launcher and aircraft, that is released at the desired launch point. The model can also simulate a 'free' launcher, in which the aircraft is free to lift off the ramp when it has attained sufficient speed. The simulation model also has the capability to simulate rocket assisted takeoff, removing the need for a launch ramp.

The atmospheric model contains steady state wind components, turbulence spectra (based upon Dryden spectra shown in MIL-F-8785C [1]), gust components and windshear elements which are based upon the effects of the ship airwake and ocean surface effects. These approximations are included as there is little published data on ship airwakes (however there are current studies [5, 7]).

Further details of all the models used may be found in Crump [4, 2, 3].

3 Control Objectives

When launching any aircraft, several objectives arise. The first and main objective is to maintain a positive altitude. Several other sub-objectives may also be specified. The first is to gain altitude as rapidly as is safely possible. The second is to maximise the distance between the aircraft and the ship.

Whilst it is possible that the UAV mission controller is capable of launching the aircraft autonomously, it is unlikely that it will successfully fulfill the launch objectives in an optimal manner. Considering the fact that the majority of flight control in today's aircraft is digital, the addition of another controller to specifically control the aircraft during launch should not prove too cumbersome in terms of physical implementation.

The first step in the design of a launch controller is to determine the desired launch trajectory that will be followed in the nominal case (this trajectory will change according to ambient conditions). This trajectory should maintain a positive altitude at all times, with as high a rate of climb (ROC) as possible during the early stages of the flight. Maintaining this high rate of climb will require a high angle of attack, so in order to prevent stall occurring regularly (due to gusts and turbulence), this rate of climb should be reduced slightly to give a margin of safety. This rate of climb should also be a sustainable rate of climb, corresponding to a trimmed condition of the aircraft.

For the case of the UAV Ariel, a launch speed of 30 m/s with a rate of climb of climb of 6.2m/s is chosen for the launch trajectory, giving a climb angle of 12°. To impart this initial climb angle, the aircraft is launched along an inclined ramp (at 12°), with a ramp exit speed of 30m/s. For control design, this model is linearised and then reduced, removing the three location states and the yaw angle state. This reduction of states results in the controllers generated having lower order.

The other important consideration is what needs to be controlled. the main objective is to maintain a positive altitude. This implies that altitude needs to be controlled, however the accuracy of various altitude measuring devices is somewhat questionable, so controlling altitude using these devices may not be feasible. Instead, the altitude can be indirectly controlled by maintaining a positive rate of climb.

Whilst maintaining a climb angle, it is also important to maintain the aircraft's airspeed, and as such a control on the aircraft's velocity is also important. To simplify the flight condition, it is also desired that the aircraft is flying in the conventional upright position with little bank angle and sideforce. To this end, a simple bank angle control will also be implemented with a sideforce regulator (if desired these two controllers may be changed into a heading hold controller).

The control of a UAV during catapult launch is a problem involving rapidly changing dynamics over a short period of time, corresponding to the first few seconds after ramp departure, followed by a longer period of slowly changing dynamics during the aircraft climb. This problem suggests itself to a dual control solution.

A highly robust nominal controller designed using linear robust modern control theory is implemented for use when the aircraft is flying well within the linear flight regime. This controller should be capable of guiding the aircraft through the launch phase in nominal or near nominal conditions, however it is unreasonable to expect this controller to be capable of handling the rapidly changing nonlinear behaviour when the aircraft is well out of its linear flight envelope (such as when the aircraft is experiencing strong head or tail winds).

For control through this region, a novel nonlinear control design technique has been implemented to control the aircraft. This technique involves an optimisation of a desired trajectory based on the nonlinear model and then the identification of an appropriate controller.

4 Nominal Controller Design

The mixed sensitivity $\mathcal{H}_\infty$ approach is an easy to apply formulation of the $\mathcal{H}_\infty$ control design problem. This method has been used successfully for many different applications (including aircraft applications) and whilst a relatively simple member of the $\mathcal{H}_\infty$ control family, still provides reasonable performance and robustness with a simple design procedure. The mixed sensitivity $\mathcal{H}_\infty$ problem is one that involves the minimisation of a combination of different weighted transfer functions, usually involving the sensitivity function S along with others such as the complementary sensitivity function T and KS. This is technique involves adjusting the shape and magnitude of the various weights to obtain satisfactory performance of the system.

The combination selected for use is the S/KS/T mixed sensitivity approach with gust rejection properties, which includes weights upon T for tracking purposes and a weight upon KS to limit control activity. Using this approach, it is possible to limit the control signal, whilst maintaining acceptable performance in the presence of gust disturbances. This problem gives the $\mathcal{H}_\infty$ optimisation problem to find the controller which minimises:

$$\left\| \begin{bmatrix} W_1SW_3 & -W_1SG_dW_4 \\ W_2KSW_3 & -W_2KSG_dW_4 \\ TW_3 & SG_dW_4 \end{bmatrix} \right\|_\infty \qquad (1)$$

The weights use integration in W_1 to ensure no steady state error and consistent low frequency behaviour. W_2 is used to minimise the high frequency control activity, whilst not penalising low frequency behaviour. W_3 is used to scale the inputs to give desired behaviour, with a large emphasis placed upon climb angle tracking and W_4 is used to balance the emphasis between performance and gust rejection.

This controller exhibits very good linear performance with small rise times, little overshoot and very good gust rejection qualities. The controller also performs extremely well in nominal launch conditions, with low steady wind conditions. In the case of mid strength winds, the linear controller fails and launch is unsuccessful. Further results for the linear controller performance can be found in [2].

5 Trajectory Optimisation with Inverse System Identification

As stated in the previous section, the linear controller performs very well in nominal launch conditions. However, the presence of high head or tail winds during the launch process causes problems. High head winds cause a large overspeed launch condition. The controller attempts to reduce speed, and in extreme conditions, the climb performance of the aircraft is reduced. This problem is quite easy to solve using nonlinear error weighting, details of which can be found in [4].

The problem of tail wind launches however is more complicated. In the presence of large tailwinds, the aircraft airspeed is dramatically reduced during the launch process. This problem leads to aircraft stall, with the resulting aircraft motion more than likely resulting in catastrophic launch failure.

This problem has been overcome using a new control technique termed *Trajectory Optimisation with Inverse System Identification* (TOISI). This technique can be logically broken into two distinct components, the trajectory optimisation component and the inverse system identification component.

5.1 Trajectory Optimisation

The first step is to determine certain time domain constraints that must be met. In this case, this is accomplished by the following constraints

- Minimal altitude loss over first seconds of flight
- Minimum error in climb angle tracking

The first and most important of these constraints is to minimise any loss in altitude.

The aerodynamic nature of aircraft means that in low speed situations it may be necessary to reduce altitude to allow the velocity to increase to amounts necessary for a sustained climb. The first constraint emphasises that little altitude may be lost in the launch situation. The second constraint similarly ensures that the aircraft is climbing as rapidly as is physically possible.

These constraints can be expressed mathematically as a *cost function*, giving

$$\text{Cost} = 10000\left(h_r - h_{min}\right)^2 + 10\sum_{t=t_l}^{t=5}\left(\gamma_{\text{opt}} - \gamma\left(t\right)\right)t^2 \tag{2}$$

where h_r represents the height of the launch ramp, h_{min} is the minimum altitude for a flight, t_l is the launch time, γ_{opt} is the optimum climb angle and γ is the time varying climb angle over the duration of the simulation (5 seconds in this case). The altitude loss term is highly weighted and the climb angle term is time weighted.

This cost function can then be minimised using a multivariable optimisation procedure. The purpose of this optimisation and hence the optimisation variables are the necessary control inputs to minimise this cost. Intuitively this situation will require full throttle, thus removing this control from the optimisation, and as the problem is mainly a longitudinal one, the lateral nominal controller can be used to provide appropriate lateral control during the flight. This leaves simply the elevator deflection to be optimised.

Differing sample times may be utilised for the elevator deflection commands, resulting in different accuracies in the trajectory. It has been found that a sampling frequency of 100Hz provides the best results, with higher frequencies giving no improvement. The 5 second simulation results in 4.3 seconds of flight (once the launch has occurred), resulting in 430 elevator deflection variables. An optimisation of these deflections can be performed, ensuring that any physical constraints such as positional and rate saturations are included.

This optimisation is performed on the full nonlinear model, and on a Intel P3-700 computer running the MATLAB optimiser on a compiled C++ simulation model will converge satisfactorily in about 10 hours for a 100Hz sampling rate. However by first utilising lower sampling rate estimations (10Hz and 50Hz) as starting points, this time can be reduced to about 5 hours.

Several sample trajectories and elevator inputs are shown in Figure 1. These trajectories show the physical limitations of the aircraft (as indicated by the mathematical model) and indicate the best achievable trajectory. This is what the controller should achieve. A 10m/s tailwind results in no loss of altitude, a 13m/s tailwind results in no loss of altitude, however a short period of horizontal flight is necessary. Finally a 16m/s tailwind requires a small loss in altitude.

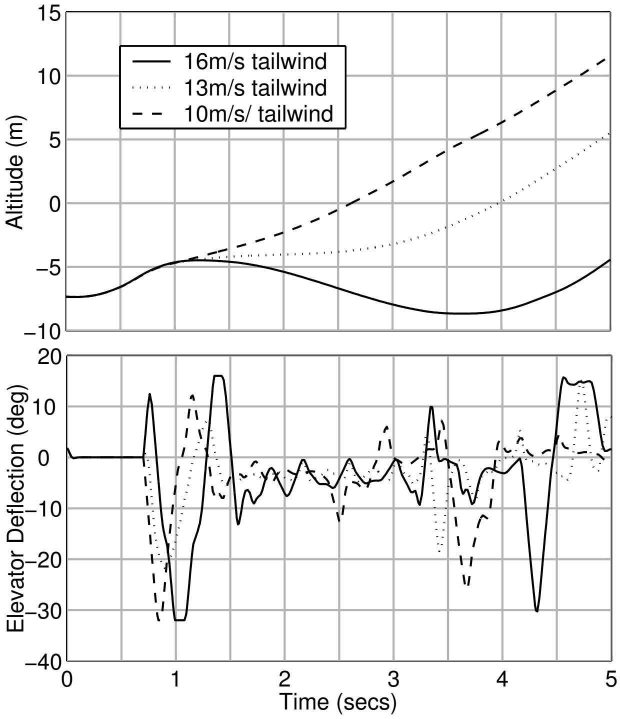

Fig. 1 Optimal launch trajectories in tailwinds

5.2 Inverse System Identification

Now given the optimal control inputs and the corresponding system outputs, a controller can be produced that generates the optimal control inputs from the system outputs. In this format, the problem lends itself to a differing use of existing system identification techniques. These techniques generally have known system inputs which generate measured system outputs, the combination of which can be used in various algorithms to predict dynamic models of the system.

A similar case exists here where the input to the controller is known (the system measurements) and the output of the controller is known (the optimal control inputs). Thus, these system identification algorithms should be able to identify the controller that generates the optimal control signals given the measured system outputs.

The system identification algorithm used for this is a modified version of the N4SID technique of Van Overschee and De Moor [11] which utilises subspace signal processing techniques to identify a dynamic model from input/output data.

The modifications to this algorithm include a stability modification suggested by Maciejowski [8] and also a multiple data set at once (MDSAO) modification to give a single best fit controller over several input/output data sets. This modification is achieved through a matrix augmentation of the input/output data within the algorithm. Due to space limitations, this modification will not be explained in detail. Further detail can be found in [2, 3].

Using this technique, many different controllers can be generated by using different combinations of system output signals as controller inputs and by using various combinations of signal delays, initial conditions and noise estimates. These controllers will have clearly stated linear performance, based upon how well they generate the optimal elevator control signals, however as is generally the case, good linear performance does not necessarily imply good nonlinear performance. In fact, a controller that almost perfectly generates the optimal elevator deflection can have extremely poor and even unstable nonlinear performance. On the other hand, a controller with satisfactory linear performance (having small errors between the identified case and the nominal case) can have excellent nonlinear performance. Due to this linear/nonlinear mismatch between controllers, many controllers can be generated, which can then be tested and either kept or discarded depending upon their linear and nonlinear performance. Due to the nature of the process, this can be achieved quite rapidly.

6 Controller Performance

Using the method of the previous sections, a controller has been generated that gives very good nonlinear performance. This controller will be used for nonlinear simulation tests of the nominal aircraft launch system, the disturbed aircraft launch system and also for robustness tests where the aircraft dynamics are perturbed.

Using the three tailwind launch cases of the previous section in the original high fidelity nonlinear aircraft model with the fully implemented nominal and inverse optimisation identification controller, the simulation results shown in Figure 2 are produced. These results show that the controlled trajectory is very close to the physically optimal trajectory and that the controller performs well in the nonlinear system. Note that this case includes the effects of sensor noise, but contains no atmospheric turbulence or gusts.

More realistic simulation results are shown in Figures 3, 4 and 5 where the aircraft is subjected to a severe turbulence level in a gusty environment with a 10m/s tailwind, headwind and crosswind respectively. A computational time delay of 0.05 seconds is also included. These results show successful launches for all three cases, however the tailwind launch case

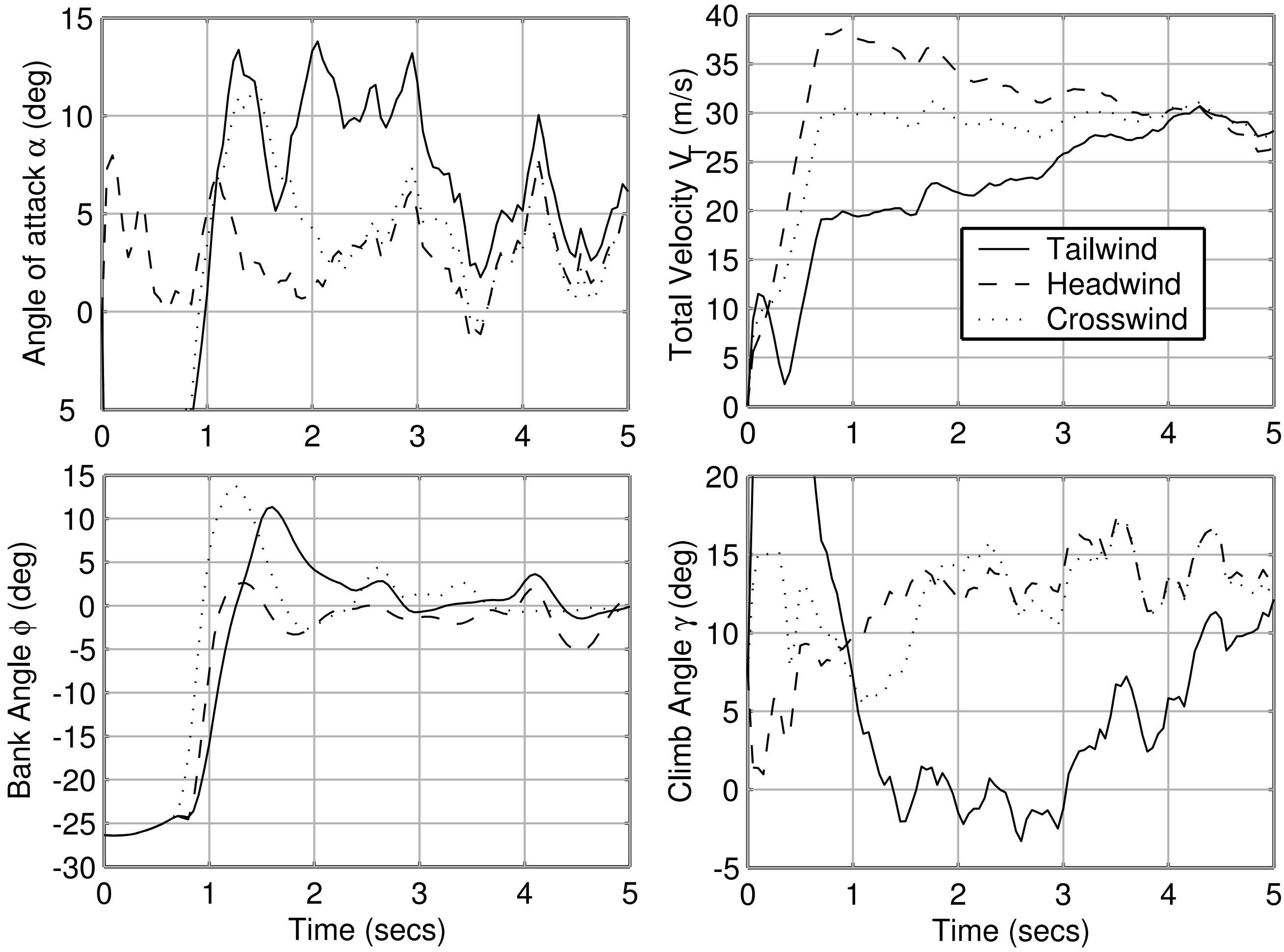

Fig. 3 Full Simulation Results

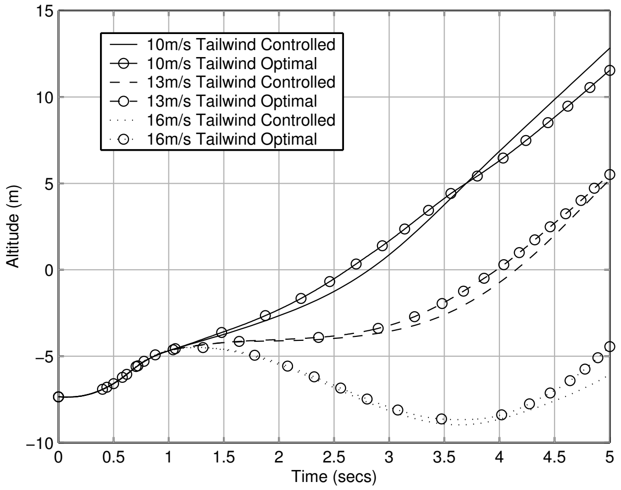

Fig. 2 Altitude

shows greater difficulty in maintaining altitude than for the previous 10m/s tailwind case. This difference is due to the turbulence and gust influence, where in this case (as shown in Figure 5) the aircraft experiences a tailwind gust during the launch process. The aircraft also experiences vertical turbulence which has a small negative impact.

The other graphs show other aircraft parameters during the launch. The tailwind launch requires a high angle of attack. The stall angle of the Ariel is approximately 12 °, thus, the aircraft actually stalls very briefly before the controller rectifies the situation. The ramp exit velocity shows the difference between headwind and tailwind case, with the aircraft in the headwind case leaving the ramp with an airspeed of about 40m/s. The aircraft in the tailwind case leaves the ramp with an airspeed of only 20m/s. The climb angle is

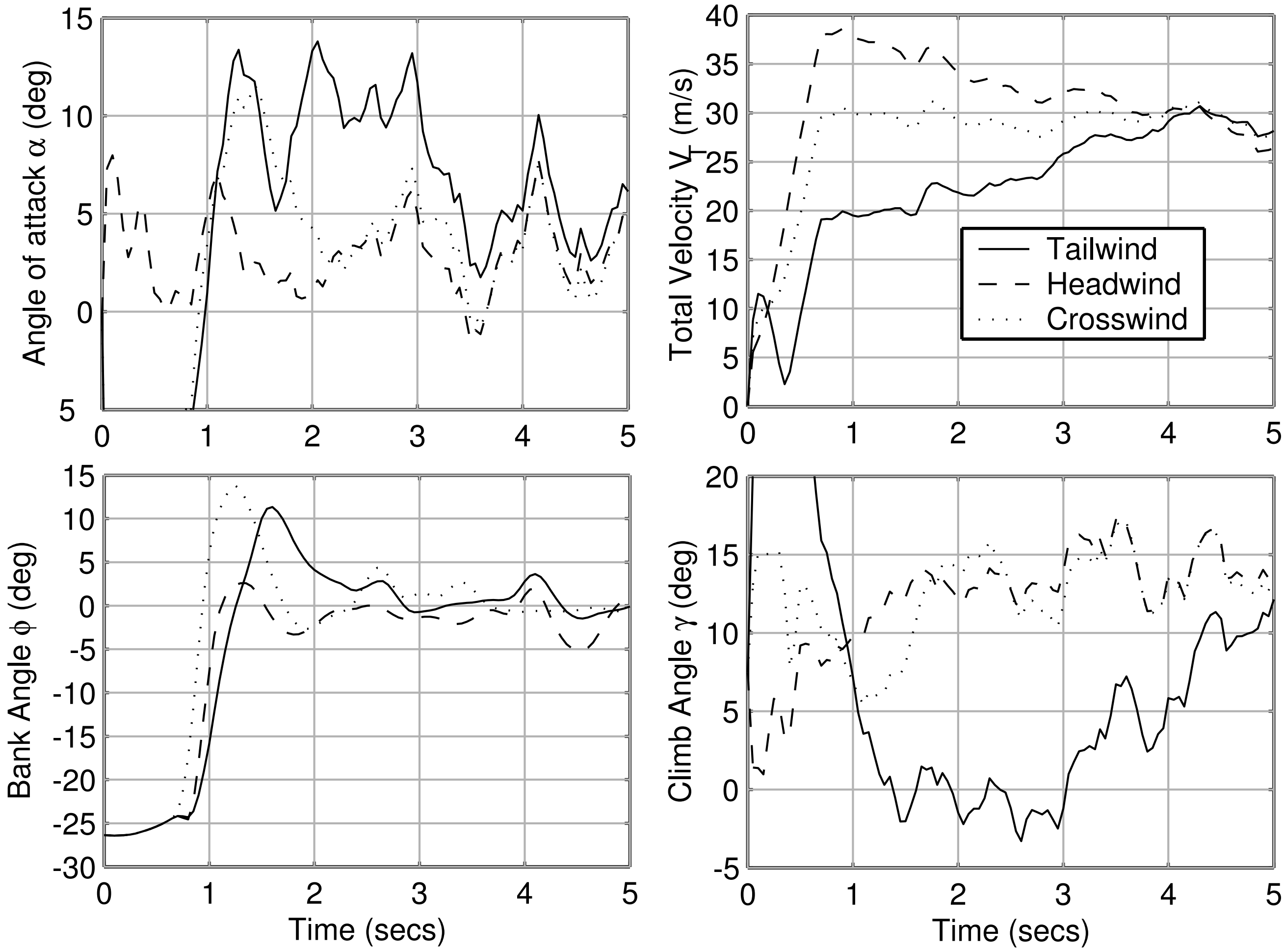

Fig. 4 Full Simulation Results

maintained well for the headwind and crosswind cases and only drops below zero for a short period for the tailwind launch. The lateral controller works well, even in the presence of large crosswinds. Finally, in the headwind case, little throttle is needed due to the large launch velocity. A significant amount of rudder control is used to control the sideforce present from the crosswind.

The other influence that must be tested is the robustness of the controller to unmodelled and incorrectly modelled dynamics. This can be partly achieved by perturbing some of the aircraft aerodynamic coefficients (by changing slopes, adding constants etc). This process has been utilised, modifying all aircraft dynamics by varying amounts, resulting in extremely good robustness of the controller. For example, the lift curve slope may be increased (by a reasonable amount) with no performance problems. Similarly, it may be reduced with no control problems, however due to the lowering of the lift force, the launch trajectory is compromised. Similar processes may be used for the other coefficients. The only problems for control exist when the moment derivatives change excessively, resulting in instability. This excessive change however is unlikely to occur if due care is taken when developing the mathematical models.

These robustness tests have been carried out over thousands of different simulation cases involving varying ship positions and wind influences. Nearly 100% of these simulations show successful launches, with the few failures explained by extremely large devia-

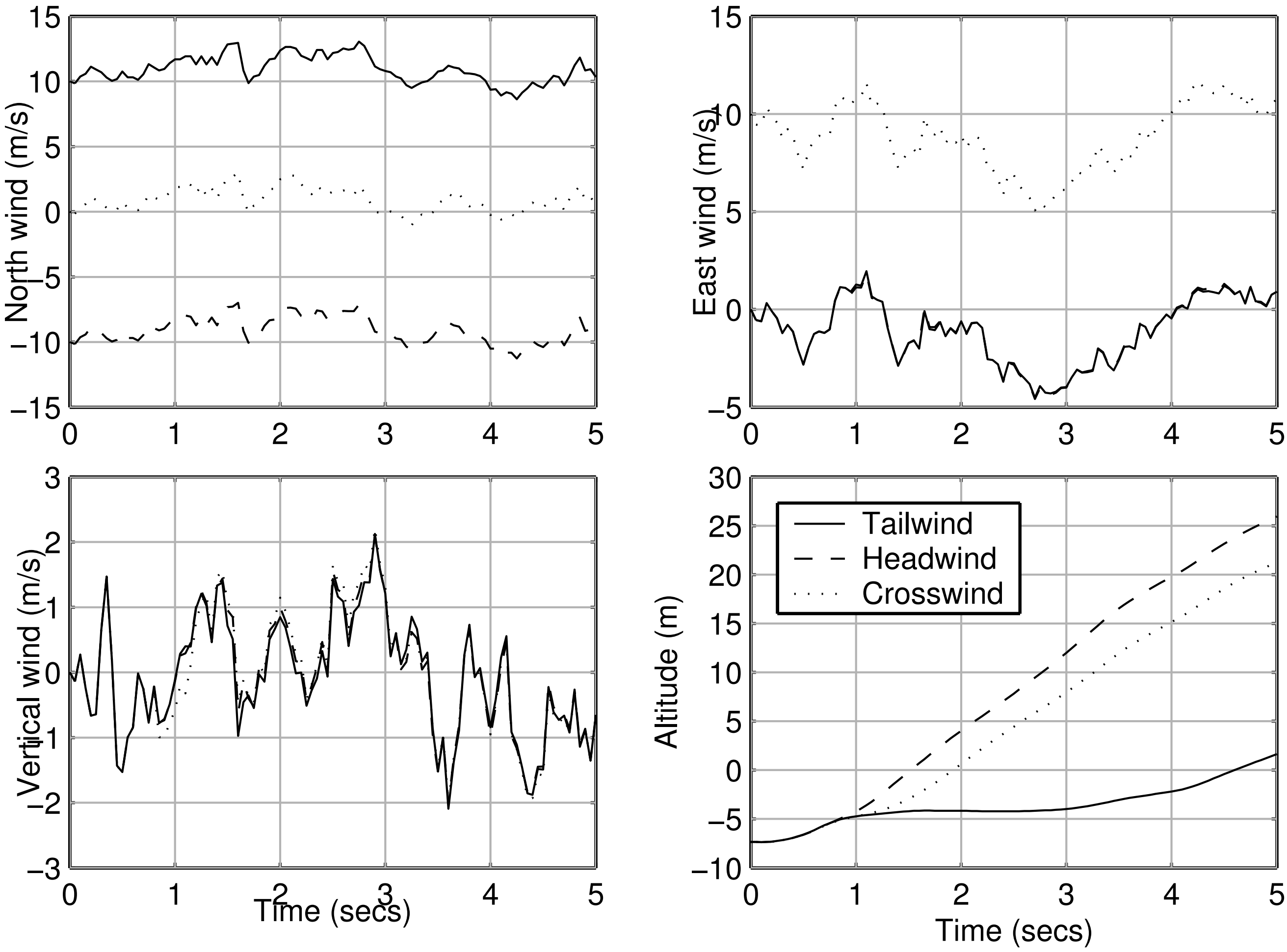

Fig. 5 Full Simulation Results

tions in aircraft parameters, excessively strong tailwinds or vertical gust and turbulence problems on ramp exit.

7 Conclusions

A controller has been developed using $\mathcal{H}_\infty$ modern control techniques and a new method termed *Trajectory Optimisation with Inverse System Identification* for launch control of UAVs in extreme conditions. This controller is found to allow the aircraft to fly extremely close to its physical limits, meaning that the launch envelope is only limited by the aircraft and not the controller. The controller has been found to be very robust to external disturbances and model uncertainty through simulation tests.

The methods used here are directly applicable for controller design for launch of conventional fixed wind UAVs and they should be easily applicable for other control situations requiring short term control of systems requiring quite stringent time domain constraints. It is the belief of the authors the the methods presented here could easily be utilised for launch and recovery control of VTOL UAVs in similar shipboard situations.

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