Predictive Control for a Tail-Sitter UAV: Final Report (Part 2)

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Highlights of New Tests since Initial Report

Since this report was released (March 2006) a number of significant testing milestones have been accomplished. The major developments are:

- Significantly improved normal hover control of the vehicle on the tether test-rig, including flights in 18 kts of wind;
- Significantly improved Model Predictive Control Flights on the tether test-rig;
- The first fully free transition flights, including transitions in both directions.

<u>This update will only detail the new information and thus should be read in conjunction with the original report to get a full picture of all activities undertaken.</u>

First some pictures…

Figure 1: T-Wing autonomous takeoff, (taken from multiple frames shot at 0.33 second intervals with Canon Digital still camera)

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14. ABSTRACT
This report covers a research project to develop a quasi non-linear model predictive control algorithm for a tail-sitter UAV.

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Figure 2: T-Wing in Horizontal Flight

Figure 3: T-Wing horizontal to vertical (H2V) transition from, (made from multiple still frames shot in 0.3 second increments by Canon digital still camera)

Figure 4: T-Wing landing while tilting into wind

Figure 5: T-Wing flying autonomously on tether test-rig using MPC controllers designed by P. Anderson. (Note Ultrasonic Wind-sensor on nose).

Flight Test Videos:

These can be seen at:

www.aeromech.usyd.edu.au/uav/twing

and navigate to the video page

Verification of Algorithms via Flight Test

A number of flight tests were carried out over the course of the last 24 months. These have mainly looked at hover mode flights on the tether test rig but as of 30th August 2006, 3 separate transition flights have been conducted and 4 transitions in each direction (vertical to horizontal, V2H, and horizontal to vertical, H2V) have been performed. Most of the hover mode flying has been done fully autonomously from takeoff to landing. The transition flights have progressed to the stage of:

- Autonomous takeoff and navigation through vertical waypoints;
- Autonomous V2H transition;
- Autonomous tracking of horizontal waypoints;
- Semi-autonomous H2V transition (pilot gives "Transition-command via stick" and vehicle performs transition);
- Semi-autonomous descent to landing, (pilot supplying velocity guidance information to low-level translational velocity controllers).

The transition flights and most hover flights have used existing non-MPC controllers, however very successful MPC hover mode flight tests have also been conducted on the tether test-rig as of July 2006. These MPC flights represent a significant improvement over the previous MPC flights conducted in 2005 and February 2006. The significant aspects that have been performed in the tests to date are set out in the following sections.

Updated Hover Tests with Standard Controllers: Moderate Winds

The Figures below (Figure 6, Figure 7 and Figure 8) show improved hover performance from the vehicle in performing the standard "+" pattern maneuver. The "plan-view" plot (Figure 6) shows the vehicle track over a full autonomous flight conducted on 13th July 2006, including pirouettes and shows no sign of biases with a 2-sigma hover precision of less than 0.74m. This flight was conducted in winds of around 6-8 knots and represents a significant improvement compared to previous flights.

For reference, the standard "+" pattern consists of the following maneuvers:

1. Climb 10 ft and hover.
2. Move in a Cross-Pattern ("+") with 8 ft legs in North, then South, then East and then West directions with belly facing North. This demonstrates vertical translations in directions aligned with major vehicle axes.
3. Reorient belly 45 degrees to point North-East.
4. Repeat Cross-Pattern with 8 ft legs in North, South, East and West directions to demonstrate vertical translations at oblique angles to the vehicle axis system.
5. Reorient Belly pointing North.
6. Perform clock-wise hesitation vertical role, stopping at each major compass point (NESW).
7. Perform similar anti-clockwise hesitation role about vertical axis.
8. Climb to 12 ft altitude;
9. Descend to 4 ft;
10. Land.

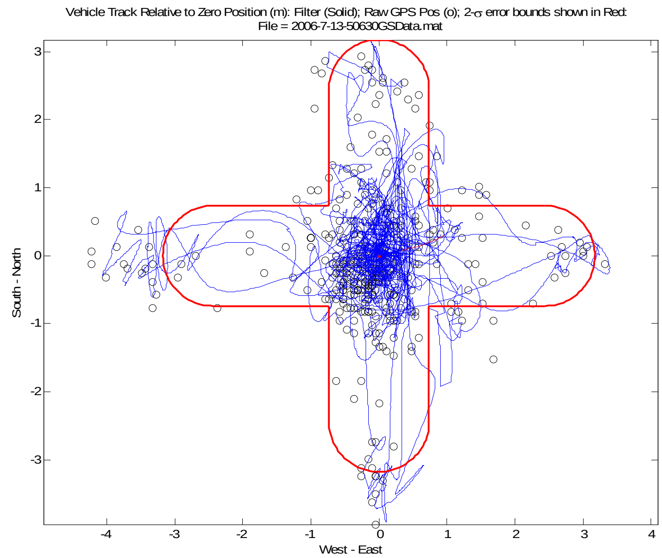

Figure 6: Plan View Position Plot for normal Hover Flight. Winds: ~6-8 kts. Plot covers full flight including both "+" patterns and both pirouettes. Red Bounding Cross indicates 2-sigma error variation for flight-path, (Sigma = 0.369m).

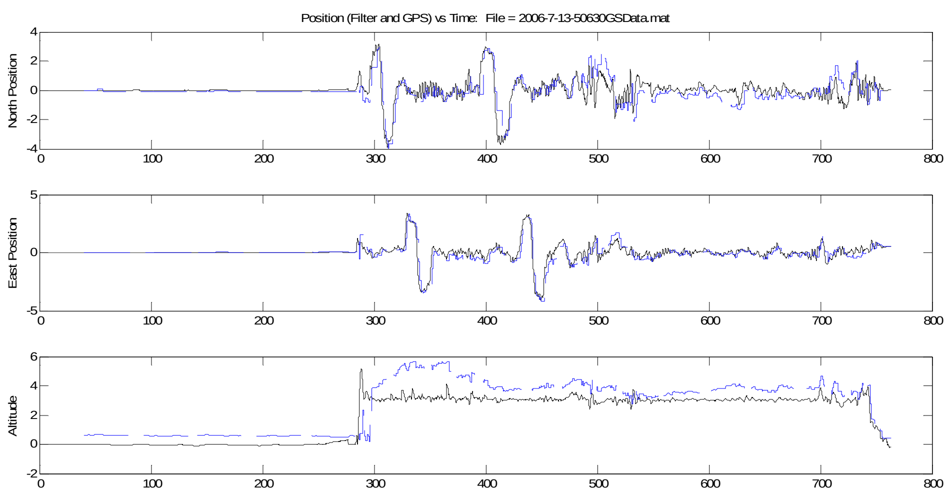

Figure 7: Position states during hover tests. Both doublets are very clear: in the first doublet the vehicle belly is facing North and the vehicle moves N→S→E→W; in the second the vehicle is skewed with belly facing North-East, but the vehicle performs the same N→S→E→W doublet very cleanly.

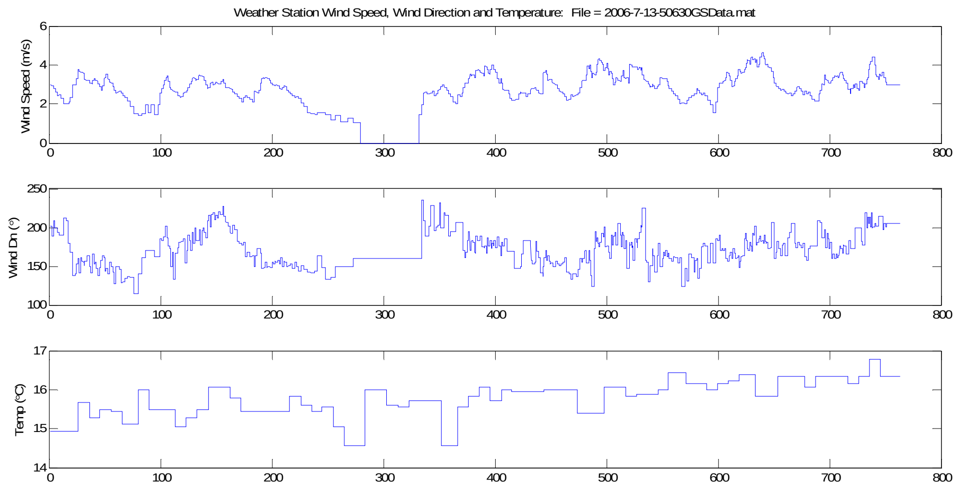

Figure 8: Wind Speed, Direction and Temperature: wind between 3 and 4 m/sec (6-8 kts) mainly from the South; approximately 16 degC; pressure altitude = -30m; (not shown here).

Updated Hover Tests with Standard Controllers: Strong Winds

The vehicle was also flown using the standard "+" pattern in winds up to 18 kts. Plots for this are shown below in Figure 9 through Figure 12. Although the precision is clearly less good than before (this time the 2-sigma error bound is 1.70m) it is not too bad considering the strength of the wind and the fact that the vehicle is only a small concept-demonstrator.

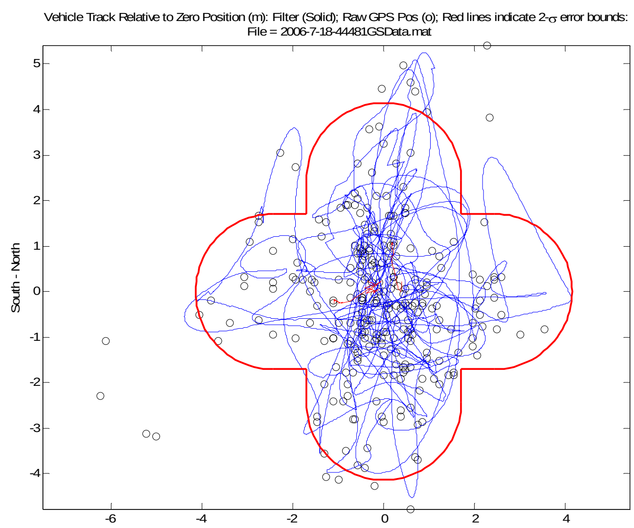

Figure 9: Plus Pattern Plan View: Strong Winds. Plot covers full flight including both "+" patterns and both pirouettes. Red lines indicate 2-sigma error bounds, (sigma = 0.853m). Winds were gusting up to 18 kts. Precision is clearly less good than before, when winds were only up to 8 kts.

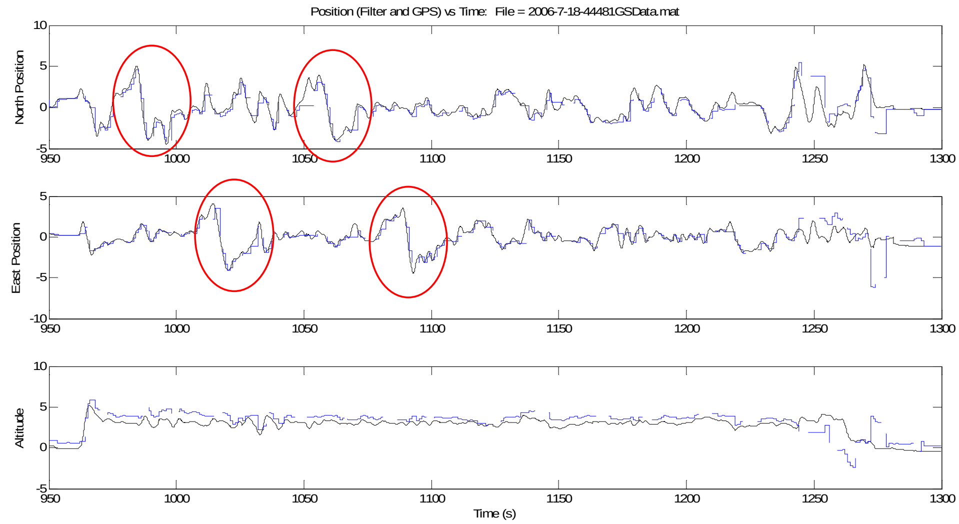

Figure 10: Plus Pattern in Strong Winds: North and East doublets indicated. Hover precision is clearly less than before but winds were up to 18 kts.

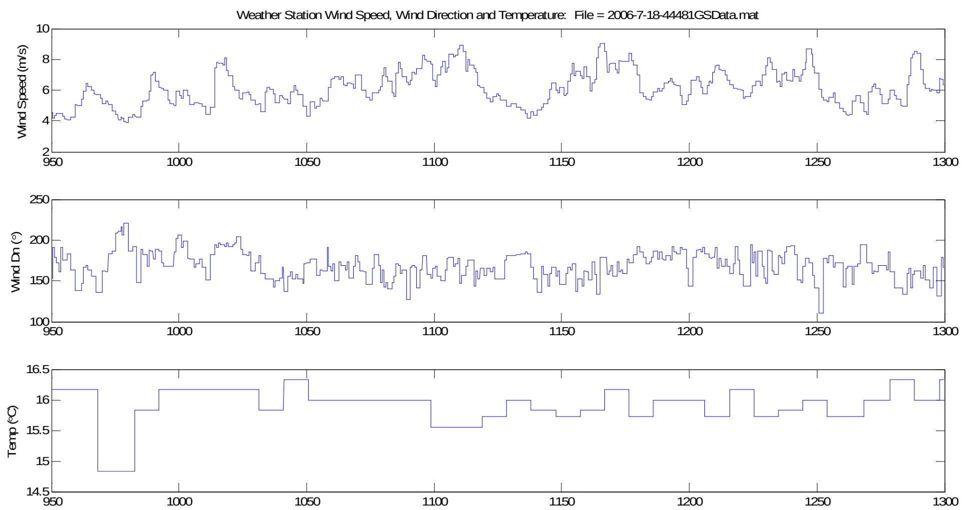

Figure 11: Speed, Direction and Temperature: Strong Winds. Wind between 4 and 9 m/sec (8-18 kts) mainly from the South; approximately 16 deg C; pressure altitude = +12m; (not shown here).

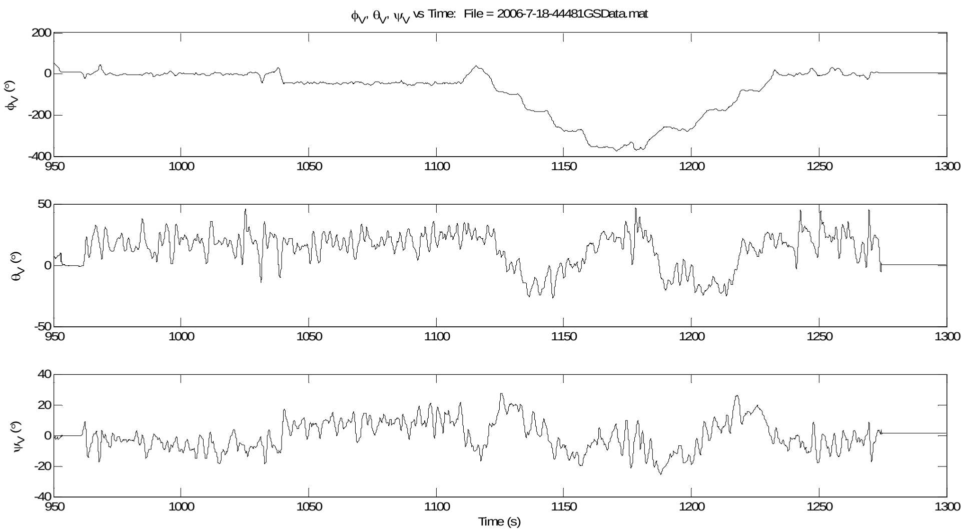

Figure 12: Vertical Euler Angles. Note that thetaV tilt angle exceeds 40 degrees at some points when vehicle was belly opposite the wind (belly pointing North, wind from the south). In other words the tilt-angle of the vehicle in the x-z plane sometimes exceeded 40 degrees from the vertical.

Full Transition Flight Tests

Full-transition flight tests were completed in August 2006. Three separate transition flights were conducted with a total of 4 transitions between vertical and horizontal flight being achieved (4 in each direction). In the last flight (30/August/2006) the vehicle did the following:

- Took-off autonomously;
- Climbed through two vertical waypoints to 300 ft altitude;
- Autonomously transitioned from vertical to horizontal (V2H) flight;
- Tracked through the first horizontal waypoint and then turned onto the second;
- At this point control was switched to semi-autonomous due to excessive altitude loss in the turn. This was later traced to a minor control system setting (saturation limits that were set too tight on an integral state in the controller); that has since been fixed.
- While in semi-autonomous flight, with the ground-pilot providing bank-angle; pitch-angle and velocity commands to the vehicle through the pilot control station, the vehicle was commanded to return to the vicinity of the runway and then to transition from horizontal to vertical flight (H2V). After this the vehicle was manually transitioned back into horizontal flight, flown in a circuit and then commanded to perform another H2V transition before descending for landing.

A composite picture of the main parts of the flight is given in Figure 13. A Picture of the flight path overlaid on the Marulan test site is given in Figure 14.

Figure 13: Composite Flight Test Picture made from shots taken during August 2006 flights.

The main outcomes of the free transition flights to date are:

- Horizontal and transition controllers work (with a small number of issues still open).
- Vertical to Horizontal transitions can be accomplished with less than 5m of altitude loss;
- Horizontal to Vertical Transitions can be accomplished in less than 50m altitude gain. Although this involves significant post-stall flight, the vehicle remains controllable, (see Figure 15).

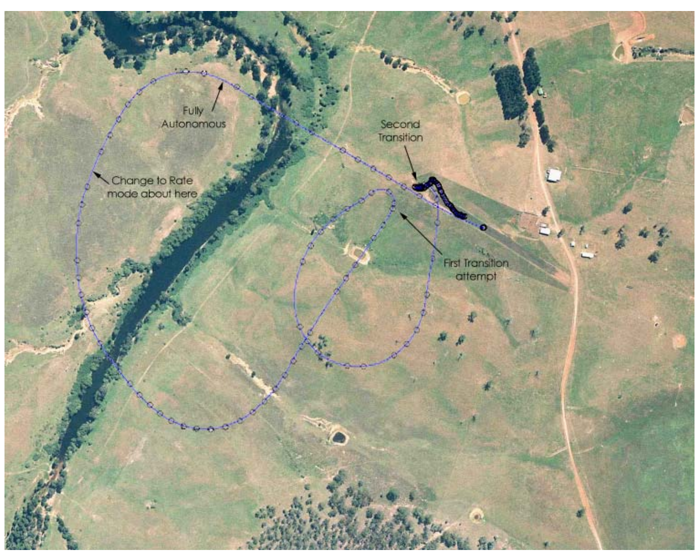

Figure 14: Rough Overlay of Marulan Map with Plan View of Flight Path

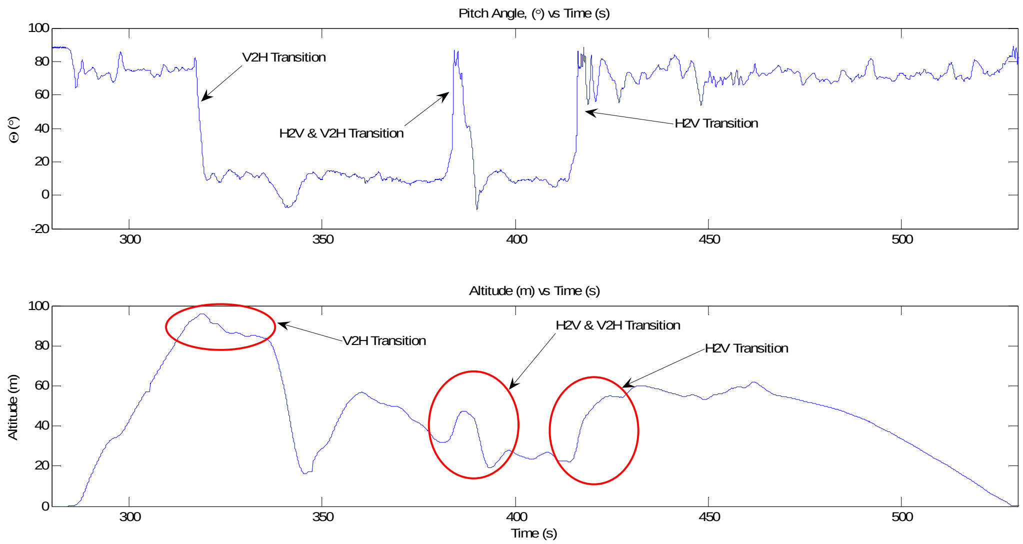

Figure 15: Altitude and Pitch Angle during 30/August Flight (2 Transitions each way). Altitude loss during the first Horizontal to Vertical (H2V) transition is ~5m; Altitude gain during the last Vertical to Horizontal (V2H) transition is ~40m.

Update on Quasi Non-Linear MPC Controllers for Vertical Flight

Previous MPC flight tests had shown a tendency for the vehicle to hold large steady state errors. The errors were of a significant enough magnitude to prevent the vehicle from reaching a waypoint and therefore it would simply get stuck hovering in one place. The most common cause of errors in MPC tracking are disturbances – both internal and external. Disturbances cause the predicted trajectory to be different from the actual trajectory for a given control signal and thus the optimal control for the assumed model might not be optimal or even sensible for the real system. In this case the disturbances were significant enough to prevent adequate tracking but not enough to cause instability.

Much of the focus of the MPC work was then in identifying and working around disturbances:

- Wind was included in simulation models and also passed into prediction model assuming constant strength and direction over the prediction horizon. This improved tracking performance of MPC controller in low-medium strength wind environments.
- The ultrasonic wind sensor was fitted to the vehicle to provide the required information for this improvement in actual flight.
- The model was found to be highly sensitive to centre of gravity position in both the x and z directions in simulation. Similar results to the actual flights could be found by altering the simulation model centre of gravity position relative to the prediction model centre of gravity position.
- The centre of gravity position was re-measured and the assumption that the z-wise cg position was aligned with centerline of the vehicle was removed. The position of the cg was measured by suspending the vehicle from the tether rope and measuring the offset distance of the known x-direction cg position from the vertical at the suspension point.

While these measures helped they were still not sufficient to allow for appropriate tracking. The use of integral control was investigated to add robustness. A primary difficulty of this is that the dynamics that cause the prediction errors are a lot more complex than simply a velocity (the MPC tracking outputs) error. Nevertheless, integral action on the horizontal and vertical velocity was attempted. The integral action builds up based on errors in the tracking. It is then scaled by evaluating the difference between the predicted position from one time-step ago and the current measured position. This scaling means that if the system is working perfectly (no prediction errors) then no integral effect is necessary and hence none is applied. As the errors become larger more integral effect is used.

There is a problem with biases using this method:

- Wind errors create biases in the earth axis frame of reference
- Centre of gravity/aerodynamic modeling errors create biases in the vehicle body axis frame of reference
- The integral effect builds up on the north, east and vertical velocities and hence is in the earth axis.
- The controller has no way of determining what amount of the bias can be attributed to wind and what amount can be attributed to modeling errors and hence when the vehicle rotates the integral effect becomes misaligned causing poor transient behaviour.

Due to these difficulties with biases the vehicle was not rotated during the flight tests on the 28th of July, 2006. This allowed for the controller to be tested with the improved robustness while avoiding the shortcomings.

Figures 16 and 17 below show the most recent and best predictive control, vertical flight to date. The vehicle ascends, performs two north facing plus patterns and then descends for landing. There was only a small amount of wind in the latter half of the flight. The controller used 8 control steps of 300ms each giving a total prediction horizon of 2.4 seconds.

Figure 18 shows the computation load diagnostics for the flight. The average calculation time for each step was approximately 65ms with a maximum of 103ms. While this is well under the allowable amount, the flight was carried out away from any constraint regions and thus the optimisation could mostly be solved quickly (usually on the first iteration).

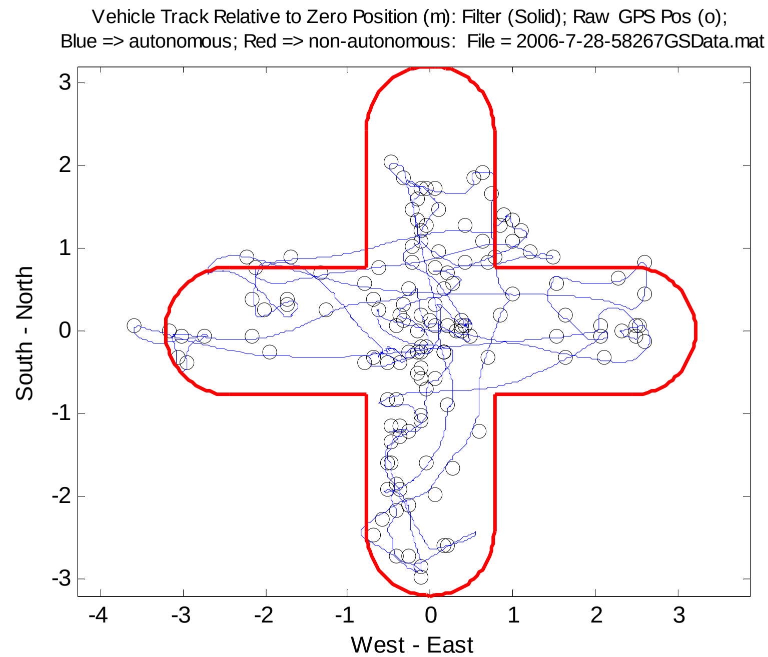

Figure 16: : Plan View Position Plot for 28/7/06 MPC Hover Flight. Winds: ~0-8 kts. Plot covers two north facing "+" patterns. Red Bounding Cross indicates 2-sigma error variation for flight-path, (Sigma = 0.386m).

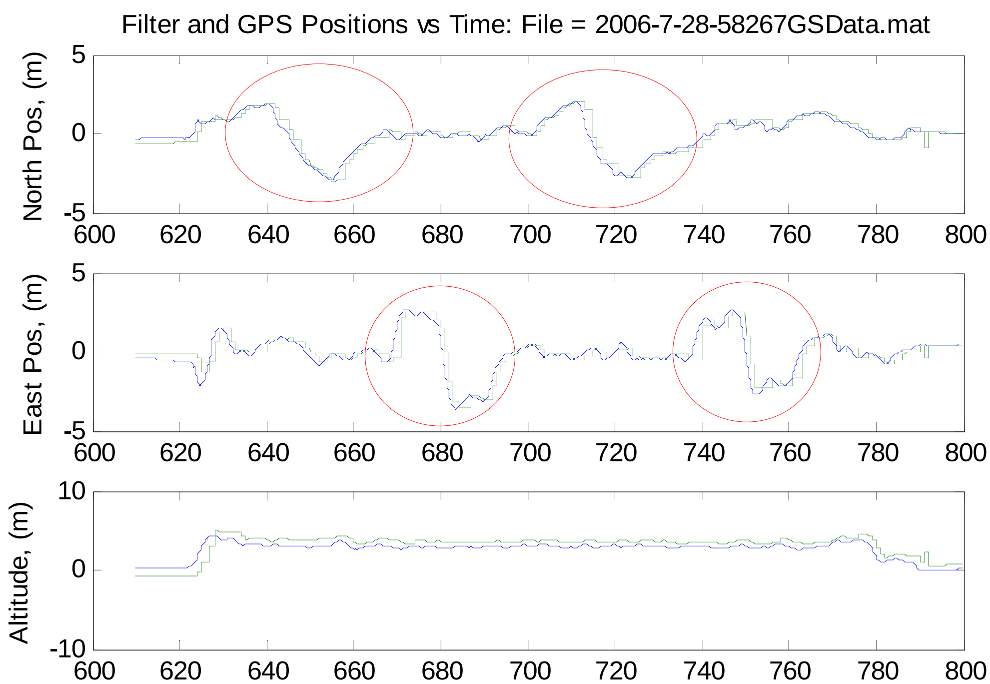

Figure 17: Plus Pattern: North and East doublets clearly visible.

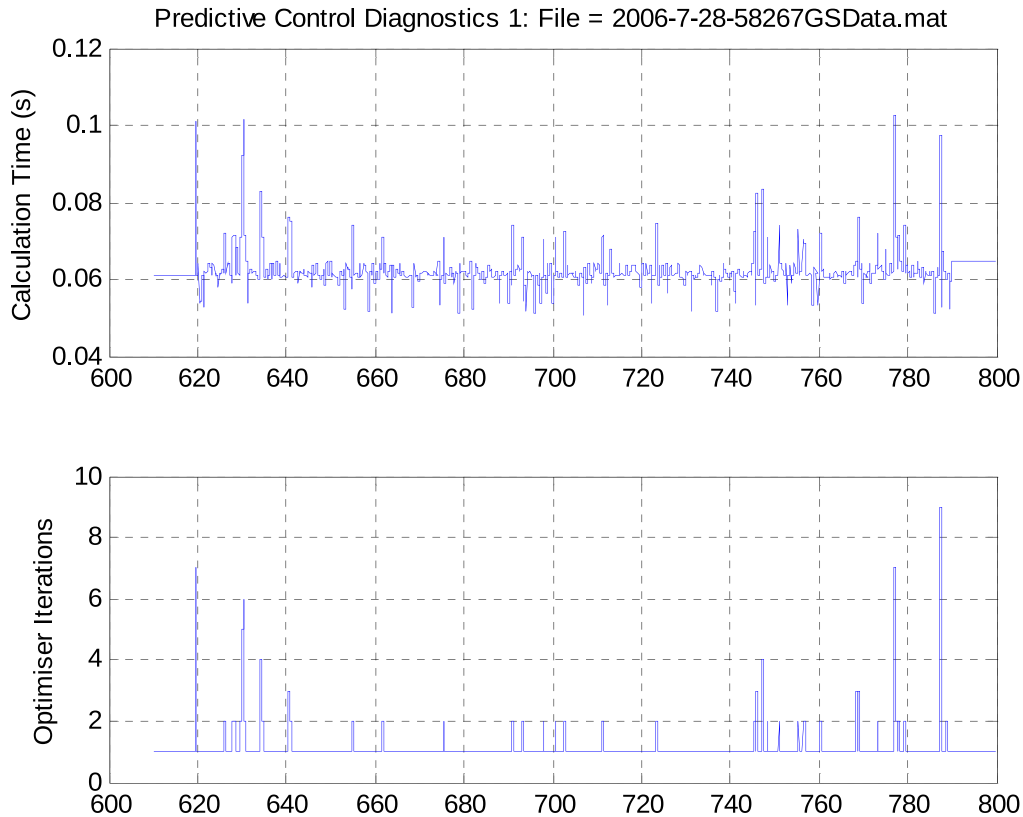

Figure 18: Computational load diagnostics for MPC hover flight, (calculation time and QP iterations)

Future Plans for T-Wing Project

The immediate future plans for the T-Wing project centre on the following activities:

- Completing a full autonomous flight demonstration for the entire flight envelope including takeoff; both transitions; and descent to landing.
- Continuing to improve the robustness and precision of the standard vertical flight hover controllers.
- Continuing MPC work, particularly for vertical flight but also for transition flight;
- Continuing integration of vision-based landing and navigation system in the vehicle (Under ARC Linkage Grant with Zylotech Pty Ltd).
- Investigation of the use of other types of true non-linear controllers for the vehicle (method of nested saturations; back-stepping controllers etc.,.)
- Investigation of alternate airframe and control concepts to enhance stealth characteristics; decrease weight and drag; and improve volumetric usage of fuselage.

During this time it is hoped that future funding and collaborative activities can be facilitated through AFOSR.