

## Title: Flight Testing of a Fixed Wing MAV in Turbulence with Open and Closed Loop Control.

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### Abstract

MAVs need to fly in complex terrains under a range of turbulent atmospheric winds. This poses control challenges which even experienced pilots find difficult to cope with. In our previous work we documented the typical turbulent wind environment of MAVs and provided data on spectral density levels, turbulence intensities, length scales and angle-of-attack fluctuations. We also performed initial open-loop flight trials under replicated turbulent conditions in a very large wind tunnel. Sensitivity to disturbance was found to be highly coupled to the MAV configuration. The most benign responses were observed in the rotary wing cases and the most violent in the fixed-wing cases.

Here we detail initial flight tests of a fixed-wing aircraft under a variety of constraints designed to limit the degrees-of-freedom to the test craft. Two purpose-designed rigs are described that; 1) permit the craft to perform pure roll, at adjustable angles of attack, and; 2) permit pitch and heave with minimal roll, lateral and fore-and-aft translations. These rigs were used to simplify the tuning of an autopilot system that could include six DOF inertial inputs, pressure sensing (via wing dynamic pressure taps) and strain measurements from spars. The results demonstrated that with no autopilot enabled control was extremely challenging, resulting in some terminal departures. However, relatively steady flight was achieved with a degree of autopilot input via roll rate tracking and damping. A series of relatively small, rapid inputs to the ailerons (at higher frequencies than could be achieved by an experienced human pilot) greatly assisted overall controllability. Furthermore the system demonstrated an ability to hold reasonably straight and level flight in relatively homogenous turbulence (approximately 8% turbulence intensity with 1m length scale) and when more discreet gusts were generated via upstream bluff bodies.

### I Introduction and Aims

MAVs have been promoted for use where direct line of sight surveillance is not generally possible. Thus their environment will normally consist of terrains which have obstacles, such as vegetation, mountains or man-made structures, including residential suburbs and city centres. The altitude at which they fly is generally low – typically in the last few tens of metres above the Earth's surface, hence MAVs are flying in the lower region of the atmospheric boundary layer (ABL). Apart from times of complete calm, the wind environment is turbulent with typical turbulence intensities of 10-50%, when measured from a fixed (Earth) reference. For over forty years Wind Engineers have recognised that turbulence characteristics should be replicated for wind-tunnel tests on buildings, mast etc., see Figure 1.



Figure 1 A Typical, Reduced Scale Building Aerodynamics Wind Tunnel Test; Note the Upstream Grid and Roughness Blocks to Generate Turbulence

When the velocity of the MAV relative to the ground is added to the (turbulent) atmospheric wind speed the relative flight speed of the MAV is found, including the relative turbulence intensity, which can vary from 0% (when flying in smooth flow) to infinity (when hovering at the mean atmospheric wind speed). However a typical relative turbulence intensity will be of the order of 5-10% for average MAV flight speeds (5-10 m/s) and atmospheric wind speed (approximately 3 m/s). These flow environments are in considerable contrast to those of larger manned craft which spend much of their time flying at relatively high speed well above the ABL, with the exception of takeoff and landing. Thus for manned craft the cruising domain is essentially smooth, with CFD or EFD replications having very low levels (or zero) turbulence.

There appears to be negligible physical or computational testing of manned aircraft in simulated turbulent environments (to replicate turbulent conditions for take off and landing). It is interesting to note that Etkin [1] considers the effect of turbulent wind on flight and suggested that the “atmospheric boundary layer wind tunnel” was a facility that could be expected to contribute to knowledge of the landing environment of manned aircraft. Etkin also surmised that flight measurements with laterally separated probes would occur, in order to add data on spanwise gradients of the flow characteristics. These comments seem very pertinent as we strive to hold a relatively stable viewing platform

from low mass, small craft (MAVs) which fly relatively slowly at low level through complex terrains close to the Earth's surface.

Our recent work has involved measurements from four probes laterally separated by a distance of about the span of typical MAVs [2], see Figure 2. We then replicated salient aspect of the relative turbulence field as experienced by a flying MAV in a very large wind tunnel. This paper gives an overview of the facility, tests and closed-loop system.



Figure 2 Outdoor Measurements of Atmospheric Turbulence at Four Laterally Separated Points in Space

## 2 The Flying Facility

We have replicated aspects of the turbulent flowfield in a large wind tunnel that has a test section dedicated to ABL simulation - the Monash University Tunnel. The facility and modifications performed to generate various intensities and integral length scales have been detailed before [x] thus only an overview is given here. The facility is sufficiently large to permit flight of MAVs of up to about 1m span. It is driven by two 5-meter diameter, fixed pitch, variable speed, axial fans situated at the start of the lower circuit.

The wind tunnel is shown in Figures 3 and 4. The wind tunnel is of the closed circuit type, and was designed as a multiple use facility with three working sections: (i) an open-jet automotive aeroacoustic test section on the lower level; (ii) a general purpose high Reynolds number closed test section, also on the lower level and (iii) a wind engineering, closed test section on the upper level.

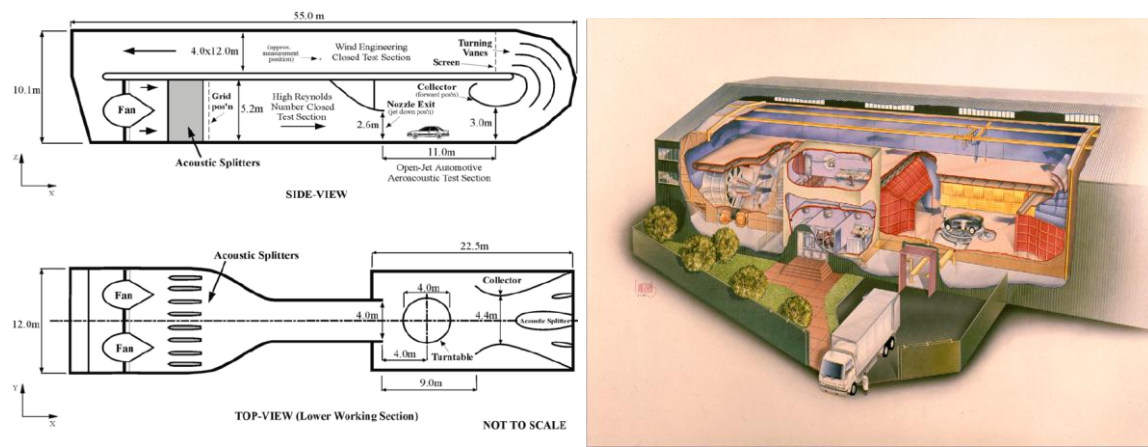


Figure 3 – Monash University Wind Tunnel

The open-jet automotive aeroacoustic test section provides a low turbulence level area for testing in relatively smooth air (longitudinal turbulence intensity  $\sim 1.5\%$ ). It also offers the opportunity for MAV flight testing including the ability to fly from the relatively stationary air (in the plenum chamber) into the jet, thus permitting a step change in flight speed – from either side of the jet, or from above, see Figure 3.

As the focus of our work is to understand the effects of turbulence the majority of tests were carried out in the wind engineering section on the upper level of the tunnel. This has a 4-meter high by 12-meter wide by approximately 50-meter long test section and an 8m diameter turntable. It is commonly used for simulations of the ABL in wind engineering studies. The wind engineering test section can be configured to give a wide range of turbulence characteristics by changing the screens at the entrance of the section, combined with changes to the lower part of the tunnel. As well as the conventional method of utilising grids, other changes include varying the nozzle exit elevation and the collector position. These changes permit the generation of turbulence intensities up to 25% in the wind engineering tests section, with longitudinal integral length scales of up to 1.7m. For the tests described here it was configured to give a longitudinal turbulence intensity of 7.5% and a longitudinal integral length scale of 1.21 m.

## 2 Flight Tests

A wide range of open-loop flying tests have been undertaken in the facility – both in smooth and turbulent flow. When undertaken in turbulent flow it is necessary to exert considerable control inputs in order to hold the craft within the confines of the test section. These have been documented in our prior work and include fixed and rotary craft of various scales [X]. Here we give an overview of the first of a series of closed loop tests on a fixed wing craft.

The aircraft used was a commercially-available recreational radio-controlled aerobatic design – a Flash Expanded Polypropylene (EPP) model from Northeast Sailplane Products. This is a highly aerobatic model with close to neutral stability and possesses very large

control surfaces. The EPP structure is stiffened with carbon-fibre which give much-needed resilience when subject to the rigours of testing in turbulent flow.

### 3 Potential Control inputs for Closed Loop

As well as the pilot inputs, several other inputs were considered and are shown in Figure 4.

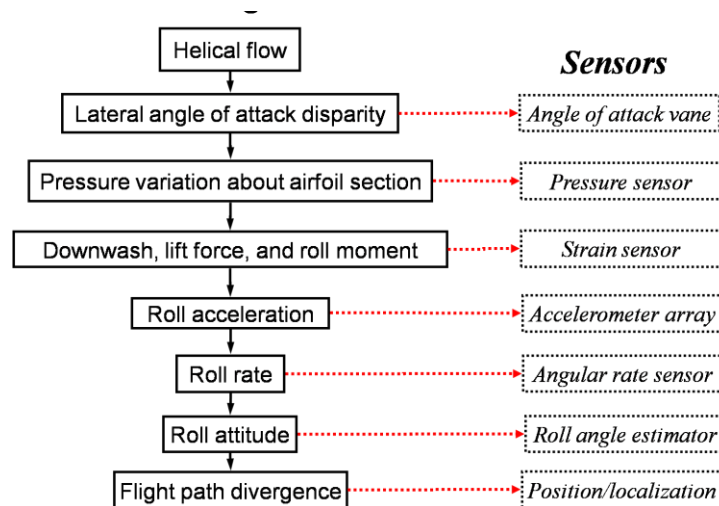


Figure 4 Potential Inputs for a Closed-Loop System

Our on-going research is involved with evaluating all of the potential sensory inputs listed in Figure 4. However here we concentrate on closed-loop control utilising purely inertial sensors combined with pilot inputs. The aircraft was equipped with instrumentation permitting the measurement of actuator position and aircraft response. The system was modular and used separate devices for sensing, data measurements, and data storage. An Atmel microcontroller (MCU) provided the overall system control, timing, and user interface. The MCU sampled from an analog to digital converter unit sampling at 100Hz, which had a 12-bit resolution and supported 16 analog input channels using a sequential multiplexer to capture the relevant piloted, response, and disturbance behavior. A tri-axial linear accelerometer and two dual-axis angular rate sensors generated analog voltage outputs measured by the data board. Single-pole analog RC filters were used on each of the 16 input channels to filter noise and vibrations from the flight data measurements. A characteristic frequency of 5Hz was used to permit measurement of relatively rapid responses while attenuating higher frequency electrical noise and mechanical vibration induced by the motor and propeller rotation. The choice of the filter characteristic frequency was based on the expected pilot input frequency and the associated aircraft dynamic rates.

Servo position was determined for ailerons, elevator, and rudder control surfaces by measuring the analog voltage of the center pin on the position feedback potentiometers in each servo motor. These potentiometers were used

internally for closed-loop position tracking and provided a convenient measurement of the output arm motion.



Figure 5 Rigs Used for Isolating a) Roll Inputs, and; b) Pitch and Heave Inputs

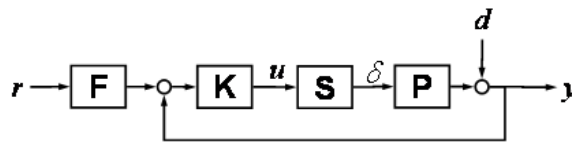


Figure 6 Closed Loop Model

The above model depicts the



Figure 7 Closed-Loop Flight Into Deeply Stalled Conditions