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Turbulence Mitigation for Aircraft in Urban Environments

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14. ABSTRACT
The PI and collaborators were interested in testing the hypothesized advantage of sensing flow disturbance before initiating an inertial response. The PI successfully completed flight trails in wind tunnels and in atmospheric turbulence. Their mitigation system reduced aircraft roll by up to 50%. In addition to the final report, the PI has 10 publications and/or conference proceedings as a result of the grant.

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Final Report for USAF AOARD FA2386-15-1-4001

Turbulence Mitigation for Aircraft in Urban Environments

16 February 2018

CONTENTS

1 DOCUMENT OVERVIEW

This report details the research performed to further develop a turbulence detection and rejection system for Unmanned Air Vehicles (UAVs). The grant has now finished although we are pursuing further avenues in the area as well as seeking funding. The research is part of a larger program at RMIT aimed at enabling safe UAV operation in urban environments and is strongly aligned with the recently-formed NATO RTO AVT-282 group which is tasked with identifying the worst case gust encountered by micro air vehicles. A prototype system, suitable for UAV, has already undergone extensive research, development and flight-testing supported by prior USAF grants.

The system demonstrated it could significantly improve the steadiness of small aircraft in the presence of high levels of turbulence and potentially could improve flight path tracking, fatigue life and aerodynamic efficiency. There is also potential to reduce the size, cost, weight and power for micro aircraft carrying optical payloads, through removing the need for expensive gimbal-stabilisation systems required to mitigate the adverse impact of turbulence on sensors.

2 PERSONNEL

Prof Simon Watkins and Dr Abdulghani Mohamed

Note: Grant has been used entirely to partly support Dr Mohamed's salary and he is now employed entirely by RMIT University. We are continuing the work on an ad-hoc basis and pursuing further funding opportunities for a postdoctoral fellow.

3 BACKGROUND

Unmanned Air Systems (UAV) are particularly suited for covert information gathering at low altitudes. However, their operational capability is limited in windy conditions and for missions in the vicinity of turbulence-generating objects such as large structures or rough terrain. Figure 1 depicts the complexity of atmospheric turbulence close to the ground (note the person on left for indication of scale). Particularly challenging to UAV flight is the vorticity evident one-third of the way along the length of the bubble.

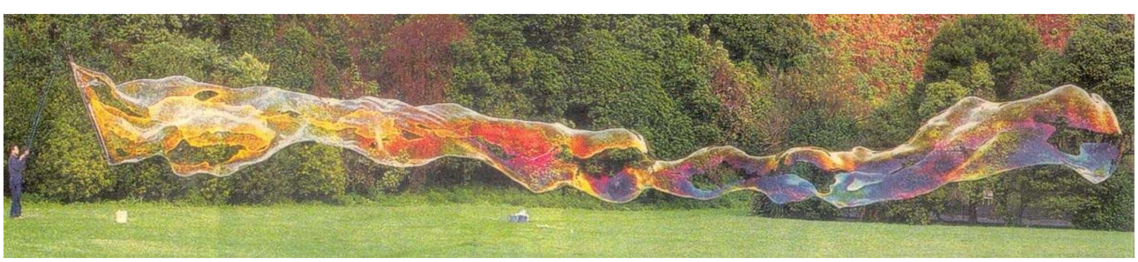

Figure 1 The longest bubble in the world (courtesy Alan McKay, copyright Garry Norman)

3.1 OUR PRIOR WORK

The team has performed prior research characterizing the nature of turbulence away from local effects at varying elevations and in a variety of terrains including cities. These turbulence characteristics have been replicated in very large wind tunnels to enable instrumented flight trials of UAVs under "repeatable", yet turbulent, conditions. Background research, sponsored by prior USAF grants, detail the measurements of Atmospheric Boundary Layer (ABL) turbulence relevant to Micro Air vehicles (MAVs) including replication in the largest wind tunnel in the southern hemisphere. A report can be found here :http://mams.rmit.edu.au/cibbi0b6g34o.pdf

Flight trials then compared human control, augmented with varying degrees of autonomy. Trials were focussed on understanding the relative merits of aircraft size and type; fixed, rotary and flapping. Trials were also undertaken to understand if the interactivity permitted with flapping flight in the natural world is a pre-requisite to holding a sufficiently stable viewing platform for sensors. The complexities involved with holding a relatively stable flight path were examined via subjective feedback from pilots and with data from on-board acquisition systems. We demonstrated that a closed-loop, on-board control system based on inertial measurements units (IMUs) could hold fixed wing UAVs reasonably stable in moderate levels of turbulence. This raised the possibility that flapping flight might not be needed at smaller scales and whether a better bio-inspired system based on fixed wing aircraft instrumented to "feel" their way through turbulent air could offer better stabilisation than conventional IMUs used on current aircraft.

4 OVERVIEW AND AIMS (*AS PER WHITE PAPER*)

The research detailed in this report and associated peer-reviewed papers tests the hypothesized advantages of sensing flow disturbances ***before*** they initiate an inertial response (i.e. time-forward sensing) and involve integrating on-board sensing to turbulence mitigation strategy. Experiments will include; wind-tunnel and real world flight-testing under challenging turbulence conditions. The work will utilise a fixed wing craft UAV, and will compare various turbulence sensing control architectures with:

1) Conventional inertial measurement systems (IMUs)
2) Novel upstream velocity sensing

The hypothesis of this research is that sensors providing "time-forward" advantages should provide significantly better stabilisation and require lower controller power input. Preliminary results from recent wind-tunnel tests of a turbulence mitigation system that is based on measuring upstream velocity perturbation (via multi-hole pressure probes, see Figure 2) have shown superior performance over traditional IMU-based systems and have enabled reasonably steady flight in high turbulence levels, see:
http://www.youtube.com/watch?v=cHuQE4cXml8&feature=share&list=PLucuqNQqkIAKk_tJtM1 Hhttp://www.youtube.com/watch?v=cHuQE4cXml8&feature=share&list=PLucuqNQqkIAKk_tJtM1H-KIflzPUXYYbOKIflzPUXYYbO

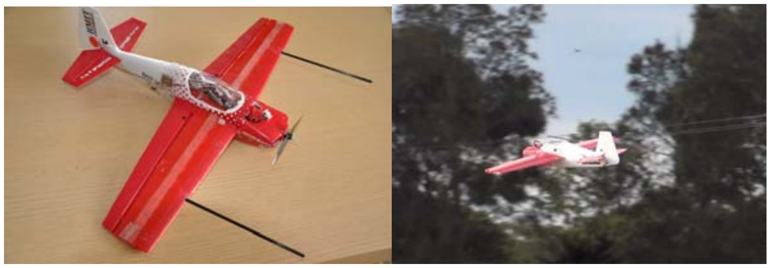

Figure 2: Prototype pressure-based system implemented on a micro unmanned aircraft

The following outlines the phases, tasks, and timeline associated with the research:

Phase1:

1. Investigating accuracy of pressure-based flow sensors in measuring turbulence
2. Use real-time data from pressure-based flow sensors within an "outer-loop" turbulence mitigation strategy
3. Testing the turbulence sensing and rejection system in:
    a. small-scale turbulence (artificially replicated in wind tunnel)
    b. large-scale turbulence (artificially replicated in wind tunnel)
    c. outdoor large-scale atmospheric turbulence
4. Benchmarking the turbulence rejection system with traditional attitude control systems

Phase2:

1. Investigating novel actuation techniques for enhanced actuation bandwidth
2. Investigating autonomous path-planning to determine optimum flight path through complex flow fields by:
    a. avoiding turbulence and;
    b. taking advantage of large upward moving gusts (i.e. updrafts)
3. Flight testing an autonomous MAV capable autonomously navigating through high levels of turbulence while exploiting favorable gusts (i.e. updrafts) to fly more efficiently.
4. Reviewing alternate state of the art flow sensors

ID	Task Name	Start	Finish
1	**Phase 1**	1/05/2015	29/04/2016
2	Study accuracy of pressure sensors for inflight turbulence measurement	1/05/2015	1/07/2015
3	Utilise real-time flow measurements within a turbulence mitigation control strategy	3/07/2015	3/12/2015
4	Flight testing the developed turbulence sensing and rejection system	1/12/2015	29/04/2016
5	**Phase 2**	29/04/2016	1/05/2017
6	Investigating novel high-bandwidth actuators	29/04/2016	1/08/2016
7	Investigating autonomous path-planning for navigation in complex flow fields	1/08/2016	30/09/2016
8	Flight testing a MAV with autonomous turbulence navigation capability	3/10/2016	6/04/2017
9	Review alternate state of the art flow sensors	6/04/2017	1/05/2017

Figure 3: Project timeline

5 WORK TO DATE

To date, phase 1 has been completed including publishing the results in peer-reviewed publications (see Section 8).

Successful flight trials have been conducted in repeatable turbulence within wind tunnels and also outdoors in atmospheric turbulence. The turbulence mitigation system significantly reduced aircraft roll perturbations by up to 50%. However when traversing in high levels of flow unsteadiness (gusts) inherent in the flows in very close proximity to buildings and other infrastructure the aircraft's stability is still significantly challenged. This has been correlated with limitations in control authority and control actuator rapidity.

6 FUTURE PLANS

Phase 2 has started whereby we are exploring means to increase the rapidity and control authority of aircraft actuation in turbulence. After preliminary experimentation Peizo-based actuators were deemed unsuitable for small scale aircraft due to technological limitations (poor deflection, max deflection speed limited by resonance of structure, high voltage). Alternatively leading edge control surfaces are being investigated for more rapidity and control authority. A PhD thesis (supervised by the authors and funded by the Australian Federal Government and Defence Science Technology Institute, DSI) started in April 2016 to investigate the use of leading edge control surfaces for mitigating turbulence disturbances.

As per the timeline, we are also exploring bio-inspired flight path planning in urban environments by avoiding turbulent regions and biasing flight path toward favourable regions (updrafts).

Preliminary results show the feasibility of utilising Computational Fluid Dynamics (CFD) as cost maps for path-planning algorithms. A publication outlining these results is currently being compiled.

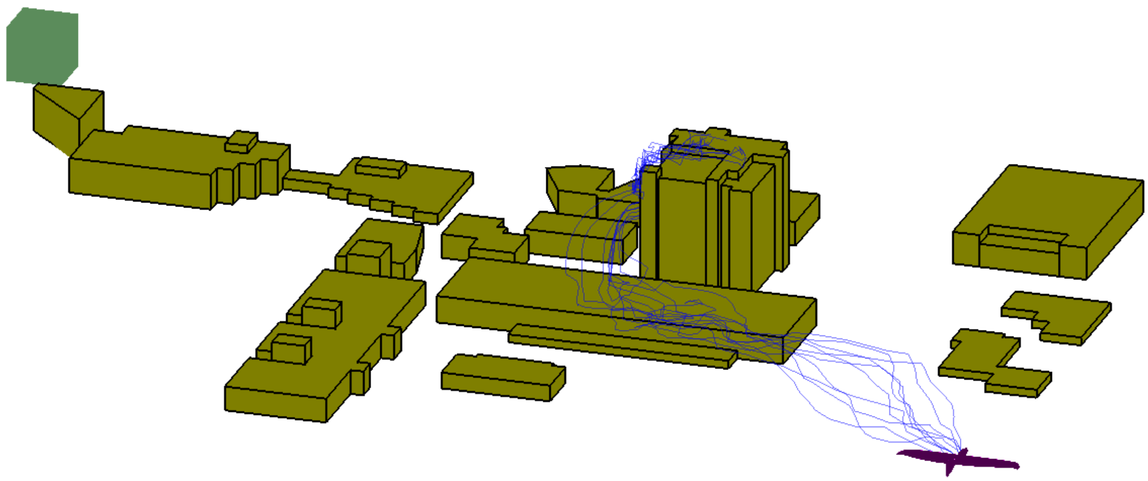

Figure 5: Path-planning Simulations in Urban Settings

As part of the NATO RTO AVT-282 group (which is tasked with identifying the worst case gust encountered by micro aircraft flying in close proximity to buildings) we are planning a series of simulations and experiments of the turbulent atmospheric boundary layer and its interaction with buildings in an urban, complex terrain. Several papers have resulted describing work to date [1-6]. Subsequently an extensive review paper is currently being compiled to explore this area focussing in what might constitute a worst case gust when flying very close to buildings and structures. Flight into shear layers has been identified as the "worst case" perturbing condition and subsequently the authors have attempted to numerically compute the gust shape as perceived from a vehicle flying through it (see figure 6 - 7). Preliminary results show a large change in lift coefficient in a short time (>1s).

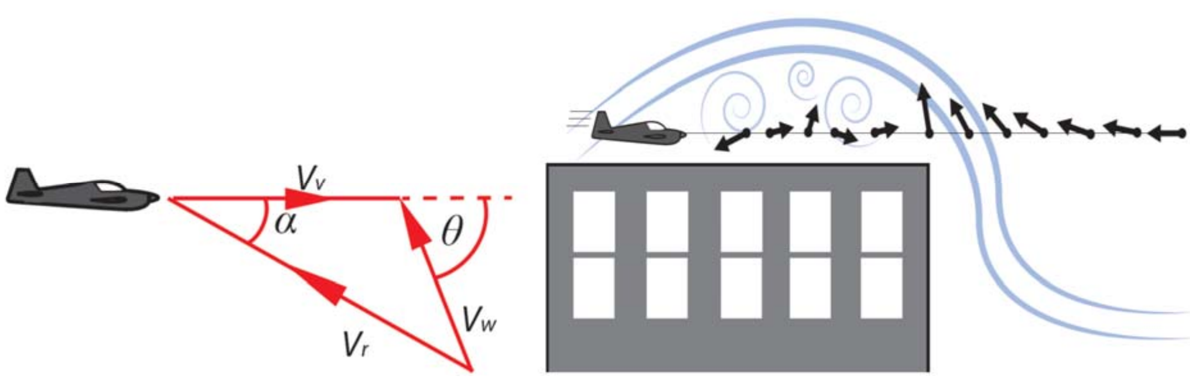

Figure 6: Path-planning Simulations in Urban Settings

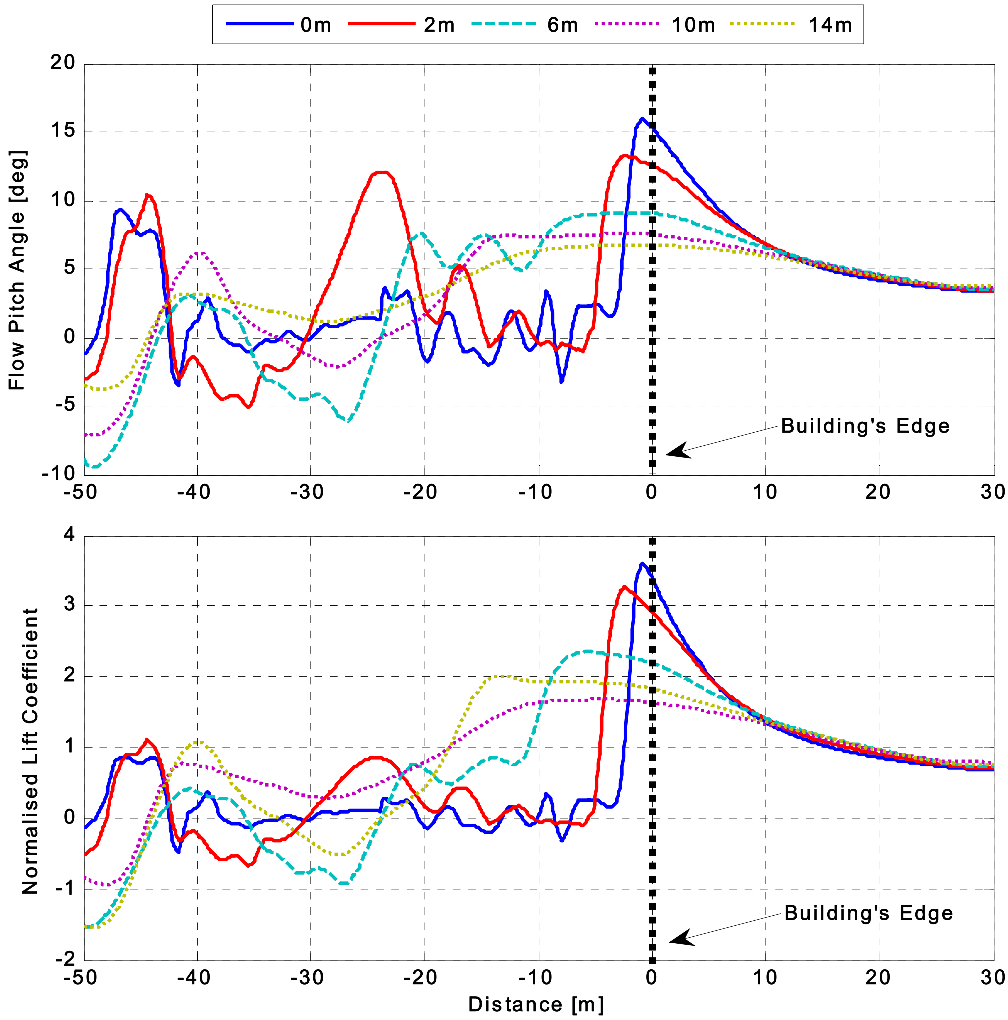

Figure 7: Path-planning Simulations in Urban Settings

7 CONCLUSION AND FUTURE WORK

The project funding period has now ended and the work was on time and cost. Several journal papers have been published and more are on-going (please see below).

Currently working with the Oxford Animal Flight Group on a proposal to study the kinematics of Falcons and Kestrels in turbulent flight in an effort to understand how they can wind hover in such challenging conditions. Furthermore a lab visit has been planned in March 2017 from Bristol University (A. Prof Shane Windsor) to study how birds utilise favourable wind phenomena for energy efficient flight path trajectories. Through modelling the flight paths of birds

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