Emulating avian orographic soaring with a small autonomous glider

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Emulating avian orographic soaring with a small autonomous glider

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Keywords: micro air vehicle, autonomous systems, soaring, flight, unmanned aerial vehicle, wind hovering

Supplementary material for this article is available online

Abstract
This paper explores a method by which an unpowered, fixed-wing micro air vehicle (MAV) may autonomously gain height by utilising orographic updrafts in urban environments. These updrafts are created when wind impinges on both man-made and natural obstacles, and are often highly turbulent and very localised. Thus in contrast to most previous autonomous soaring research, which have focused on large thermals and ridges, we use a technique inspired by kestrels known as ‘wind-hovering’, in order to maintain unpowered flight within small updrafts. A six-degree-of-freedom model of a MAV was developed based on wind-tunnel tests and vortex-lattice calculations, and the model was used to develop and test a simple cascaded control system designed to hold the aircraft on a predefined trajectory within an updraft. The wind fields around two typical updraft locations (a building and a hill) were analysed, and a simplified trajectory calculation method was developed by which trajectories for height gain can be calculated on-board the aircraft based on a priori knowledge of the wind field. The results of simulations are presented, demonstrating the behaviour of the system in both smooth and turbulent flows. Finally, the results from a series of flight tests are presented. Flight tests at the hill were consistently successful, while flights around the building could not be sustained for periods of more than approximately 20 s. The difficulty of operating near a building is attributable to significant levels of low-frequency unsteadiness (gustiness) in the oncoming wind during the flight tests, effectively resulting in a loss of updraft for sustained periods.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$C_{L_{\text{max}}}$</td>
<td>Maximum lift coefficient</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>$C_L$</td>
<td>Lift coefficient</td>
</tr>
<tr>
<td>$C_Y$</td>
<td>Side force coefficient</td>
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<tr>
<td>$C_m$</td>
<td>Pitching moment coefficient</td>
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<tr>
<td>$C_I$</td>
<td>Roll moment coefficient</td>
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<tr>
<td>$C_n$</td>
<td>Yaw moment coefficient</td>
</tr>
<tr>
<td>$dC_{D_{\text{f}}}$</td>
<td>Drag coefficient increment due to sideslip</td>
</tr>
<tr>
<td>$dC_l$</td>
<td>Lift coefficient increment due to sideslip</td>
</tr>
<tr>
<td>$dC_{D_{\text{d}}}$</td>
<td>Lift coefficient increment due to elevon deflection</td>
</tr>
<tr>
<td>$dC_{m_{\text{d}}}$</td>
<td>Pitching moment coefficient increment due to elevon deflection</td>
</tr>
<tr>
<td>$h$</td>
<td>Height</td>
</tr>
<tr>
<td>$I_{ax}$, $I_{ay}$, $I_{aw}$</td>
<td>Longitudinal, lateral, vertical moments of inertia</td>
</tr>
<tr>
<td>$I_{xx}$, $I_{yy}$, $I_{zz}$</td>
<td>Mass moments of inertia</td>
</tr>
<tr>
<td>$I_{xz}$</td>
<td>Mass product of inertia</td>
</tr>
<tr>
<td>$l$, $m$, $n$</td>
<td>Roll, pitch, yaw moments</td>
</tr>
</tbody>
</table>
1. Introduction

Micro air vehicles (MAVs) are increasingly being used for low-altitude operations in urban environments, for tasks such as surveillance, infrastructure inspection, law enforcement, and search and rescue. As MAVs decrease in size and weight, their range and endurance become increasingly limited by the energy density of current battery technology. Until energy density is significantly increased, MAV designers and operators must look to other means of improving range and endurance. One such strategy is to extract energy from the surrounding environment, and in particular from the airflow.

It has long been known that birds conserve energy by soaring—using updrafts present in the environment to reduce the energy expenditure needed to maintain or increase altitude (Akos et al 2010). Thermal updrafts originate from thermal non-uniformities, localised regions where the ground is heated to a greater extent than the surrounding area, causing the air to rise buoyantly. Despite the fact that thermal updrafts originate at ground level, they can extend upwards to significant heights (on the order of 5 km (Allen 2006)). Updrafts are also generated when a horizontal wind impinges on an obstacle and is forced upward; this phenomenon occurs in the vicinity of both natural (e.g. hills and cliffs) and man-made structures. This upward motion of air is known as orographic lift. Birds commonly utilise thermal and orographic updrafts, performing both types of ‘static’ soaring to harvest environmental energy (Langelaan 2007).

In contrast with these methods, it is also possible to extract energy from sheared horizontal flows without significant updrafts through ‘dynamic’ soaring (Barnes 2004, Lawrance and Sukkarieh 2009, Akos et al 2010, Sachs et al 2010, Ariff and Go 2011, Bird et al 2014). Such wind fields typically occur above ridges, over large ocean waves, or in atmospheric wind-shear lines. While soaring extracts energy from the mean flow, it is also possible to extract energy from fluctuations in the oncoming flow (i.e. from turbulent kinetic energy), as theoretically demonstrated by Patel and Kroo (2006) and Dmitriev and Jenny (2013). However, given the random nature of atmospheric turbulence, it is difficult to predict how much energy will be available and hence difficult to rely on this type of energy extraction to increase endurance. While MAVs of all conventional configurations (i.e. fixed, rotary, and flapping wing) can potentially benefit from updrafts, fixed-wing aircraft are the most likely to succeed in performing prolonged soaring in typical winds with zero thrust power input. A fixed-wing MAV could sequentially exploit discrete orographic updrafts in an urban environment, using them to gain height and/or airspeed, gliding between them, and expending little or no energy. This would be akin to the way manned sailplanes fly great distances by gliding between thermal updrafts spaced kilometres apart (Reichmann 1978). Alternatively, a MAV could hold position within an updraft and, instead of using it to gain height, harvest the excess energy by wind-milling its propeller and store the energy in a battery (MacCready 1999, Barnes 2006). Orographic soaring, utilising updrafts created by both natural and man-made features, is the subject of this paper.

1.1. Previous work on autonomous soaring

The majority of previous research on soaring strategies for unmanned air vehicles (UAVs) pertains to soaring in thermal updrafts. This includes strategies for predicting the locations of thermal updrafts using weather and topographic data (Bohner et al 2011), autonomously searching for thermal updrafts using flight-path feedback (Wharington 1998, Allen and Lin 2007, Edwards 2008, Akhtar 2010) or forward-looking sensors (Akhtar 2010), cooperative searching for thermal updrafts (Andersson et al 2009), trajectory optimisation within thermal updrafts (Qi and Zhao 2005), and trajectory optimisation through
known velocity fields containing thermal updrafts (Wharington 1998, Langelaan 2008, Kagabo and Kolodziej 2011, Al-Sabban et al 2012). Most of these investigations are limited to simulation only; however, several authors have conducted successful flight tests (Allen and Lin 2007, Edwards 2008, Palmer et al 2011). Allen and Lin (2007) achieved a flight of over 60 min duration with a model sailplane and were able to demonstrate height gains of about 500 m in strong updrafts; and Edwards (2008) demonstrated 5.3 h of autonomous flight with the same sailplane, which travelled 63 km from an initial altitude of 140 m above ground level. These investigations used a relatively large aircraft (with a 4.2 m wingspan), which cannot be classed as a MAV. Palmer et al (2011) retrofitted the control system of a typical small surveillance platform (with a 2.3 m wingspan) with an autonomous soaring capability and demonstrated the capturing and tracking of relatively weak, drifting thermal updrafts, in which the aircraft was able to gain over 100 m in height without propulsive power.

Trajectory optimisation for orographic soaring has been explored by Langelaan (2007). Optimal trajectories were calculated for two unmanned aircraft flying along a 60-km-long constant-height ridge. This problem is similar to the one considered here, although in urban environments the objects generating orographic updrafts (built structures) are typically much smaller laterally, making autonomous orographic soaring in urban terrain more challenging (as discussed in section 1.2).

The potential to exploit orographic soaring with small MAVs flying upwind of buildings was examined by White et al (2012a), who undertook a series of wind-tunnel tests with a 1:100-scale model of a 38 m (width) × 38 m (length) × 43 m (height) building on the Royal Melbourne Institute of Technology (RMIT) campus (known as ‘building 201’) to quantify the velocity field on its windward side as a function of oncoming mean wind speed. The sheared velocity profile of the atmospheric boundary layer (ABL) was replicated in the tests, as was the turbulence intensity. The horizontal and vertical components of the wind velocity field measured by White et al (2012a) are shown in figure 1. The vertical velocity component was found to reach up to 50% of the unperturbed upstream wind speed at building height (denoted by \(V_0\)). A follow-on theoretical study by White et al (2012b) concluded that the flow field would be sufficient to keep a MAV aloft. A flight test to prove this theoretical finding has not yet been attempted.

1.2. Unique challenges of autonomous urban soaring

Path planning, state estimation, flight control, and obstacle avoidance each present significant challenges for autonomous orographic soaring with a fixed-wing MAV in an urban environment.

The horizontal extent of thermal updrafts used for soaring is usually large enough for an aircraft to enter the updraft and to fly in a circular pattern to gain altitude. Diameters of several hundred meters are typical (Childress 2010). Due to the large size of the thermal updraft relative to the aircraft, simple control strategies may be adopted without the need for a sensor measuring the local flow field. Staying within the updraft and flying a circular pattern, or any other optimal pattern, without significant changes in airspeed is usually possible, because the aircraft’s airspeed is
typically much greater than the mean horizontal wind speed. In contrast, for orographic soaring in front of a building or hill, the mean horizontal wind speed is likely to be a significant fraction of a MAV’s airspeed, as an appreciable oncoming wind speed is required to generate a suitably strong updraft. The extent of the updraft is also limited both horizontally and vertically, to a relatively small region upstream of and above the windward side of the building or hill (as illustrated in figure 1). These restrictions mean that adopting guidance and control strategies used for autonomous soaring in thermal updrafts will not be suitable for orographic soaring. For example, flying a circular pattern to gain altitude may take the MAV outside of the small orographic-updraft region. Further, if the aircraft turns downwind at too low a height, it may be carried away by the wind and be unable to return to the updraft without significant energy expenditure.

For orographic soaring, one way to stay within an updraft is to fly into the wind at the mean wind speed, effectively hovering above a spot on the ground, while gaining altitude. Depending on the match between the MAV’s airspeed and the oncoming wind speed, side-to-side movements may be necessary to prevent the MAV moving too far upstream and out of the effective updraft area. This also complicates the planning of trajectories between these types of updrafts by adding a heading constraint to the updraft-entry phase. The aforementioned soaring behaviours are observed in kestrels performing what is known as ‘wind-hovering’, a flight mode in which the bird maintains a constant position relative to the ground while searching for prey (Henderson 2008). Birds can also change their wing shape to maintain position (using lift and drag variations for additional control). This could be replicated by a MAV through morphing wings and deployment of spoilers or flaps.

The requirement to maintain horizontal position to within a very small error presents a challenge with respect to state estimation. The MAV is effectively stationary, and hence the ground speed is negligible; therefore, the use of ground-track information to aid in the estimation of heading, wind speed, and airspeed (as is typically done with fixed-wing MAVs) is very difficult. A MAV performing orographic soaring would need to rely on air-data sensors, magnetometers, and possibly vision-based feedback to estimate these elements of the state vector (e.g. Garratt et al 2013, Ping et al 2015). Controllability during orographic soaring is also a challenge; unlike a rotor craft, lateral corrections to the position are necessarily coupled with heading changes for a fixed-wing aircraft. Longitudinal position corrections require a change in pitch attitude, which will compromise glide performance (i.e. lift-to-drag ratio).

If the oncoming flow were relatively laminar, these estimation and control aspects may not be so challenging. However, it has been established that the flow environment at low altitudes (within the ABL) is typically highly turbulent (Watkins et al 2006). This turbulence is particularly severe in built-up areas, due to vortex shedding from upstream obstacles, and contains significant energy at high frequencies and spatial wavenumbers (Watkins et al 2006). Given their low inertia, MAVs rapidly respond to these turbulent perturbations, often with large deviations from the nominal trajectory and attitude, unless drastic control inputs are given. For larger aircraft these perturbations are effectively damped by their slower dynamics.

These challenges illustrate why it is not possible to apply existing automated guidance and control strategies developed for autonomous thermal soaring to the problem of orographic soaring. It can also be concluded that fast control and state-estimation loops, rapid actuation, and a high degree of control authority are necessary for successful autonomous soaring by a MAV in an urban environment.

1.3. Aims, scope and layout of paper

The long-term aim of this work is to improve the endurance of MAVs operating in urban environments through orographic soaring. Although previous theoretical studies by White et al (2012a, 2012b) have shown that urban wind environments may be conducive to MAV soaring in that they contain updrafts of sufficient magnitude, an autonomous control system has yet to be developed and trialled. Thus, the immediate objective of this study is to develop and flight test a system that addresses the challenges identified above and to validate the theoretical findings made by White et al (2012a, 2012b).

Specifically, the remaining sections of the paper describe the following:

- the development of a nonlinear, six-degree-of-freedom (6-DoF) model of the flight dynamics of a fixed-wing MAV based on wind-tunnel measurements and vortex-lattice computations (section 3).
- A simplified trajectory calculation and control algorithm for the fixed-wing MAV designed to gain height within an orographic updraft of limited spatial extent (section 5).
- Results from 6-DoF simulations of the MAV’s flight that indicate the controller’s performance in the updraft field in front of a gently sloping hill and in a uniform updraft field with significant atmospheric turbulence (section 6.1).
- Flight-test data demonstrating the ability of the control system to guide the MAV to autonomously gain or hold height by performing orographic soaring in front of a hill and a building in an urban environment (section 6.2).

Flight-test data presented in this paper are limited to the flight phases in which the MAV soared or attempted to soar (i.e. periods in which the aircraft
gains or maintains height in an updraft, because this is the main focus of the research. Navigation and path planning between soaring opportunities is the subject of on-going research.

2. Apparatus

2.1. MAV platform

A commercially available remote-controlled, unpowered sailplane known as the Alula (Dream-Flight, Inc.) was chosen as the test platform. It is a flying-wing design that possesses a number of desirable features, including a low wing loading (making it flyable in light winds), full-span elevons (giving it good control authority), and a foam construction (making it durable and reducing the possibility of damage to personnel and equipment). Its low mass and frangible construction were also key factors in ensuring that flight testing posed minimal third-party risk—a practical consideration in all UAV flight testing. It is also the same platform for which White et al. (2012b) estimated the glide performance, allowing for validation of some aspects of the 6-DoF model. The cavity in the Alula’s fuselage was enlarged to accommodate additional electronic components, and the loss in structural strength of the fuselage was compensated for with the addition of thin carbon-fibre straps, as shown in figure 2. The Alula has a wingspan of 900 mm, mean chord length of 186 mm, and a length of 480 mm. The mass of the aircraft including all sensors and the controller was 210 g.

All state-estimation and control tasks were performed on a DataNinja MAV control board (Shifted Dynamics, Inc.). This 36 mm × 26 mm board contains a ST Microelectronics 32 bit ARM microcontroller and an MPU-6000 inertial measurement unit (InvenSense, Inc.). The board was interfaced to a Spektrum RC receiver, an OpenLog SD card logger, a u-blox LEA-6 Global Positioning Satellite (GPS) receiver, and a Honeywell HMC5883L magnetometer. The GPS receiver and magnetometer were mounted toward the rear of the aircraft to minimise electromagnetic interference, while the remainder of the electronics were mounted in the fuselage (see figure 2).

The unmodified Alula requires a small amount of ballast in its nose to achieve static longitudinal stability; however, in the present arrangement, additional ballast was necessary to offset the positive pitching moment produced by the rear-mounted GPS receiver. While this increased the aircraft’s sink rate, when flying into stronger winds it was beneficial because it increased the airspeed at which the aircraft achieved its minimum sink rate, bringing it closer to the mean wind speed. This is demonstrated in figure 3, which shows the sink rate as a function of airspeed for different aircraft masses. These data were derived from the 6-DoF model discussed later.

To maximise rate-of-climb in an updraft of constant magnitude, the MAV will ideally be operating at the airspeed which gives the minimum sink rate. For example, referring to figure 3, at a mass of 250 g the minimum sink rate is approximately 0.42 m s⁻¹, which is achieved when the airspeed is approximately 6.3 m s⁻¹ (termed the ‘minimum-sink’ or ‘best-loiter’ airspeed of the aircraft). For the case of the MAV ‘hovering’ in an updraft with zero ground speed, this means that the incident wind speed must also be 6.3 m s⁻¹ for optimum aerodynamic performance. From figure 3, it can be seen that the penalty (in terms of sink rate) for flying at a speed significantly greater than the minimum-sink airspeed is generally more severe than the penalty of adding mass. The plot also indicates the minimum updraft speed required to effectively soar (i.e. this must be greater than the minimum sink rate). Without the additional electronics and ballast, the aircraft mass was approximately 150 g.
at which it could maintain height in an updraft of 0.34 m s⁻¹. For the results presented in this paper, the aircraft mass was 265 g, requiring a minimum updraft wind speed of 0.45 m s⁻¹.

2.2. Wind tunnel

Wind-tunnel tests were used to measure the steady-state aerodynamic forces and moments on the aircraft at various orientations to the oncoming flow, for use in the 6-DoF model. The tests were conducted in a closed-circuit, low-turbulence aeronautical wind tunnel with a 1.35 m × 1.1 m working cross-section. The typical longitudinal turbulence intensity of the tunnel has been measured previously to be around 0.3% (Sanderson 1986). Tests were performed at a speed of 6 m s⁻¹, yielding a chord-based Reynolds number (Re) of 70 000 for the Alula; for the purpose of the 6-DoF model, the non-dimensionalised force and moment coefficients were assumed to be Reynolds-number independent. To verify this assumption, several of the coefficients were measured at a Reynolds number of 140 000. They were found not to differ significantly, except when the wing was close to stall, where the increase in Re increased the maximum lift coefficient (C_{L_{\text{max}}}) by about 15%.

The aircraft was mounted via a 50 mm sting to a ATI Nano17 Titanium force/torque sensor, capable of measuring ±32 N with 6 mN resolution and ±0.2 N·m with 32 μN·m resolution along the horizontal axes (double these values along the vertical axis). The influence of the tare drag and moment of the sting was minor and was accounted for by subtracting it from each measurement. The sensor was mounted on a larger sting that could be yawed and tilted to change the angle of attack and sideslip angle (see figure 2).

2.3. Outdoor flight-test sites

Two outdoor test sites were used. The first, a hill in the suburbs of Melbourne, Australia (called 'Johns Hill'), was chosen as a relatively easy site at which to perform orographic soaring. The cross-section of the hill is shown in figure 4; this cross-section remained roughly constant for a width of approximately 200 m. The region upwind was relatively clear of trees and other turbulence-generating terrain features. As a result, this produced a wide, relatively two-dimensional (2D) flow...
field, while the gentle slope avoided the development of separation regions.

Building 201 at RMIT University, the same building studied by White et al (2012a), was used as the second test site. The northern side of the building is relatively free from large obstructions for a significant distance; thus it was decided to attempt tests in a northerly wind to minimise the turbulence in the oncoming wind. There are however several buildings upstream of building 201 that are likely to influence the flow. The position and size of these are illustrated in figure 5. The sharp geometry and limited horizontal and vertical extent of the building (and consequently the updraft field) make this site a much more difficult one at which to perform orographic soaring.

3. 6-DoF model

The development of the 6-DoF model is described in this section. The model utilises the results of wind-tunnel tests, numerical aerodynamic simulations, and experimental estimates of the MAV’s inertia obtained from measurements of its geometry, in order to predict the forces and moments (and hence the linear and angular acceleration) acting on the MAV for arbitrary incident flow angles and speeds. As is often done in 6-DoF aircraft models, rotation-rate-dependent forces and moments were estimated separately to the quasi-static forces and moments. The two are then assumed to add linearly.

3.1. Static forces and moments

Static forces and moments were estimated using results from wind-tunnel tests. Certain simplifications were made to avoid having to perform wind-tunnel tests over a full grid of combinations of angle of attack (α), sideslip angle (β) and deflections of the left and right elevons (δεL and δεR, respectively). Firstly, the lift and drag coefficients (C_L and C_D, respectively) were considered primarily as functions of α, with additive corrections for the effects of β, δεL, and δεR. The primary functions C_L(α) and C_D(α) were measured in steps of 2°, while the additive correction functions dC_L(β, α) and dC_D(β, α) were measured on a coarse α-grid (-20° to 20° in steps of 10°) at β = -25° to 25° in steps of 5°. The additive correction functions dC_L(δεL, α) and dC_D(δεR, α) were measured on the same coarse α-grid, for seven linearly-spaced deflections of the elevons between full-up and full-down. The influence of β on elevon effectiveness was taken into account by the multiplicative correction functions ηC_L(β) and ηC_D(β), which were measured at β = -25° to 25° in steps of 5°. The formulas for the total static C_L and C_D are summarised by

\[
C_L \approx C_L(\alpha) + dC_L(\beta, \alpha) + \eta_{C_L}(\beta) \cdot dC_L(-\delta_{\text{er}}, \alpha),
\]

\[
C_D \approx C_D(\alpha) + dC_D(\beta, \alpha) + \eta_{C_D}(\beta) \cdot dC_D(-\delta_{\text{er}}, \alpha).
\]

(1)

(2)

The coefficient of pitching moment (C_m) was approximated in a similar way, except that the direct dependence of C_m on β was found to be small and was thus ignored. The indirect dependence of C_m on β when the elevons are deflected was still taken into account, as indicated by

\[
C_m \approx C_m(\alpha) + \eta_{C_m}(\beta) \cdot dC_m(\delta_{\text{el}}, \alpha) + \eta_{C_m}(\beta) \cdot dC_m(-\delta_{\text{er}}, \alpha).
\]

(3)

Both angle of attack and elevon deflection were found to have a negligible influence on the side-force coefficient (C_F), the latter was thus taken to be a function of β alone. Therefore,

\[
C_F \approx C_F(\beta).
\]

(4)

The yaw- and roll-moment coefficients (C_n and C_b, respectively) were considered to be primarily functions of β; thus, C_n(β) and C_b(β) were measured on a β-grid of -25° to 25° in steps of 5°. The additive correction functions dC_n(α, β) and dC_b(α, β) were measured on a coarse α-grid of -20° to 20° in steps of 10°, on the same β-grid. Elevon corrections were measured in the same manner as was done for C_L and C_D, with the exception that β was found to have little impact on elevon effectiveness in roll and yaw, so this effect was ignored. Thus,
\[ C_n \approx C_n(\beta) + dC_n(\alpha, \beta) + dC_n(\delta_{\text{el}}, \alpha) \]
\[ + dC_n(-\delta_{\text{el}}, \alpha) \]  
\[ C_l \approx C_l(\beta) + dC_l(\alpha, \beta) + dC_l(\delta_{\text{el}}, \alpha) \]
\[ + dC_l(-\delta_{\text{el}}, \alpha) \]  

For the purpose of the 6-DoF model, cubic Hermite polynomials were used to interpolate between the sample points for all of the aforementioned functions. Measurements for two cases (\(\alpha = 0^\circ\) and \(10^\circ\); \(\beta = 0^\circ\)) were repeated seven times to derive error estimates; \(\pm 2\sigma\) over the repeated measurements was 0.023 for \(C_l\), 0.0035 for \(C_{\text{mp}}\), 0.02 for \(C_{\text{mr}}\), 0.0012 for \(C_{\text{m}}\), and 0.0041 for \(C_n\).

### 3.2. Rate-dependent forces and moments

Rotation-rate-dependent force and moment coefficients were estimated using the Athena vortex lattice (AVL) code (Drela and Youngren 2014). The three-dimensional (3D) geometry of the Alula aircraft was laser-scanned to capture the precise chord shape, planform, and twist distribution of the main wing and tail, and these data were imported into AVL. The discretisation used for the vortex-lattice analysis is shown in figure 6; the nose was ignored for the purposes of this analysis as it was not expected to contribute significantly to the rate-dependent forces and moments.

The 3D model was also used to obtain the inertia tensor. The fuselage was assumed to have constant density, this being calculated by dividing the mass by the volume calculated from the 3D model. Electronic components were represented in the 3D model as cuboid solids, the size and weight of these being determined by measurements of each component.

As is typically done in 6-DoF models, rotation-rate-dependent force and moment coefficients were assumed to add linearly to the quasi-static coefficients. These were also assumed to be linearly proportional to the rotation rates, with the constants of proportionality (i.e. aerodynamic derivatives) being functions of \(\alpha\), and independent of \(\beta\) and \(Re\). A number of the cross-coupling derivatives were found to be negligible and thus omitted from the model. The effect of the following derivatives were included: \(C_{\text{mp}}\), \(C_{\text{mr}}\), \(C_{\text{mp}}\), \(C_{\text{mr}}\), \(C_{\text{el}}\), and \(C_{\text{np}}\) (where standard notation is used in that \(C_{\text{X}}\) represents the non-dimensionalised derivative of \(X\) with respect to \(Y\); see for example Nelson 1997). The non-dimensionalisation scheme used here follows that of Nelson (1997).

### 3.3. Summary of aircraft dynamics

The non-dimensional aerodynamic derivatives and inertial properties of the aircraft are summarised in

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**Figure 6.** Vortex-lattice discretisation showing distribution of bound vortex legs (—) and trailing vortex legs (––).
models consist of a heavily damped short-period oscillation \( \omega_p \approx 10.2 \text{ rad s}^{-1} \) and an almost neutrally stable phugoid mode \( \omega_h \approx 1.80 \text{ rad s}^{-1} \). Lateral-directional modes consist of the typical Dutch roll \( \omega_n \approx 4.83 \text{ rad s}^{-1} \), spiral \( \tau \approx 6.42 \text{ s} \), and roll-subidence \( \tau \approx 0.06 \text{ s} \) modes. Natural frequencies and time constants were calculated directly from observation of the model’s response to small perturbations to the trimmed condition. These modes may be observed graphically in the responses to symmetric elevon-step and differential elevon-singlet inputs shown in figure 7 and are typical of fixed-wing aircraft (Nelson 1997).

4. State estimation

The attitude-estimation technique was based on that of Mahony et al (2008), whereby gyroscopic measurements are integrated to produce an estimate of the direction-cosine matrix (DCM), then the estimated error (based on an accelerometer and magnetometer measurements) is fed back through a proportional-integral (PI) controller to correct the DCM estimate. The proportional part of the feedback results in the nonlinear analogue of a complementary filter, while a very small integral gain eliminates the effect of any long-term gyroscope bias. The technique used here differed slightly in the way magnetometer and accelerometer data were fused: the rotational error derived from the magnetometer measurement was split into two components, one parallel to the estimated gravity vector and one perpendicular to it. Different weights were applied to each component in the feedback loop. A much larger weighting was applied to the rotation component parallel to the gravity vector, so that the magnetometer was ‘trusted’ more for the estimation of heading than for pitch and roll angles.

Position estimation was performed by combining the Euler-angle estimates from the aforementioned attitude-estimation algorithm, accelerometer measurements, and GPS-position measurements in an extended Kalman filter (EKF). The Euler angles were considered as known inputs subject to independent random errors with constant variance. The UDUT\(^T\)-factorised form of the filter, along with the modified Gram–Schmidt orthogonalisation procedure for prediction and the sequential-measurement-update method given by Bierman (1977) were used to avoid round-off errors encountered with the original form of the filter due to the use of single-precision arithmetic. As opposed to tracking accelerometer bias as part of the state vector, the accelerometer data were filtered with a 2nd-order Butterworth high-pass filter to
remove any long-term bias before being input to the EKF. Although this results in a suboptimal estimate, it has the benefit of filtering out the gravitational acceleration, which may bleed into the horizontal-acceleration components due to errors in the Euler-angle estimates. The corner frequency of the filter was 0.05 Hz.

A block diagram of the overall state-estimation algorithm is shown in figure 8.

5. Control algorithm

5.1. Trajectory determination
In formulating the control algorithm, a priori knowledge of the wind-velocity field was assumed in determining the optimum location for soaring. An alternative would be to use feedback from total-energy measurements to probe the field for the optimum soaring location, but this was not considered here. While this has been done successfully in thermal updrafts (Allen and Lin 2007, Edwards 2008), it can be argued that the limited extent of the updraft region, proximity to the ground, and high turbulence intensities characteristic of urban orographic-soaring sites would prohibit such a strategy for orographic soaring. For example, if the MAV were flown into the vicinity of an updraft, but not close enough to the updraft core such that height can be maintained, the MAV would likely lose too much height before finding a location at which height gain is possible. It is also possible that a wind gust with a relatively long timescale may be falsely interpreted as a time-averaged updraft. Such a feedback system could be used to augment the method used here, but is left to future work.

For a given aircraft mass, ‘soaring-obstacle’ shape, and wind direction, the optimum soaring trajectory is dependent on the mean wind speed. To narrow the range of possible trajectories, one may start by considering only regions of the flow in which the MAV is able to gain height while maintaining its horizontal position relative to the ground (and therefore the updraft field). As a counter example, there may be a region of the flow in which sufficient updraft is available for the MAV to gain height while flying at or near its minimum-sink speed, but the velocity magnitude of the wind field at that point is such that the MAV would have to be moving forward or backward relative to the ground (and therefore the updraft field) in order to do this. Sustained ‘hovering’ flight in such a region would therefore not be possible. Transient maneuvers through such regions are possible, but these must be done at an expenditure of energy. Thus when determining the desired trajectory, it is logical to rule out paths that transit these regions.

To demonstrate these concepts, a ‘feasible soaring region’ has been calculated for the centrelime of building 201, using velocity data from the wind-tunnel tests of White et al (2012a), and the 2D cross-section of Johns Hill. The velocity field for the latter case was determined by a potential-flow calculation. The potential-flow approximation, while not possessing the fidelity of a Reynolds-averaged Navier–Stokes simulation, is believed to be warranted given the gentle slope of the hill, the fact that the area of interest is in a favourable pressure gradient, and the fact that no significant obstacles are present in the upstream vicinity to cause areas of flow separation. Also, in the case of the building, it should be noted that, at least in the case of an oncoming wind perpendicular to the upstream face, the greatest updrafts will occur along the centreline. Thus, it is this plane that should be considered for soaring trajectories. The results for different mean wind velocities are shown in figures 9 and 10. For building 201, the reference velocity is defined as the upstream velocity at building height; while for Johns Hill, it is defined as the velocity 10 m above the hill’s crest. From figures 9 and 10, one may observe that for both cases there is an optimal wind speed at which the region’s vertical extent is greatest; this will change with aircraft mass as a result of the optimal ballasting problem discussed earlier. These figures also show the ceiling (i.e. the highest point of the feasible soaring region).

Once the feasible soaring region has been determined, a trajectory through this region can be calculated. An optimisation algorithm could be employed to find the optimum trajectory from a given starting point, utilising flow-field data and the aerodynamic properties of the MAV. However, a simpler method is proposed here, which will not give the optimum
trajectory for an arbitrary starting point, but should give results close to it under certain assumptions.

Firstly, the ‘constant-horizontal-position rate-of-climb’ (referred to as RoC) is calculated for each point in the feasible region. This is simply the difference between the updraft velocity \( w \) and the MAV’s sink rate when flying at zero ground speed (i.e. the sink rate when the airspeed is equal to the wind speed):

\[
RoC(x, y, z) = w(x, y, z) - R_s(|V(x, y, z)|), \quad (7)
\]

where \( R_s(V) \) gives the steady sink-rate for a certain airspeed. Values of RoC within the feasible soaring region can be used to generate the desired trajectory as follows. If the horizontal component of the MAV velocity with respect to the ground is assumed to be negligible in comparison to the airspeed, then the rate of climb is approximately that given by equation (7). Thus, to gain height as quickly as possible, the MAV should be kept at the horizontal location providing the maximum RoC for its current height. If RoC is considered a function of the 2D horizontal position vector \( x \) and the height \( h \), then the desired horizontal position \( x_{\text{target}}(h) \) as a function of height is given by

\[
x_{\text{target}}(h) = \arg \max_x RoC(x, h). \quad (8)
\]

The desired heading is that which points directly into the wind:

\[
\psi_{\text{target}}(h) = -\tan^{-1}(v, u), \quad (9)
\]

where \( u \) and \( v \) are the components of the wind velocity in the \( x \)- and \( y \)- directions, respectively. A trajectory calculated in this way for the Johns Hill site is shown in figure 11.

This method does not solve the problem of optimising the trajectory from an arbitrary starting point, and does not account for turns or other accelerated motions, but it is envisaged that in the eventual application, the MAV’s navigation system will initially position it close to this target trajectory. The ‘soaring-mode’ controller (described in the next section) will then be activated, and the MAV will subsequently capture the target trajectory and gain height until it reaches the ceiling of the feasible soaring region.

5.2. Controller

A simple cascaded proportional-integral-differential (PID) controller was used to hold the MAV on the
target trajectory. It consists of a series of four cascaded PID loops for lateral-directional control and three for longitudinal (pitch) control (figure 12). The horizontal position and velocity are first transformed into a coordinate system in which the x-direction points upstream along the desired heading. The x-position error is used to generate a pitch-angle command, which is then used to generate a pitch-rate command, and finally an elevator command. The y-position error was used to generate a heading command, from which successive PID loops generate roll-angle, roll-rate, and aileron commands. Elevon commands are then created by linearly mixing the elevator and aileron commands. Horizontal velocities from the Kalman filter are used in lieu of derivative action on the outermost loops, while feed-forward action was used on the innermost loops to improve pitch- and roll-rate tracking.

The inner loops provide rate damping and disturbance rejection, while the outer loops correspond to the way a human pilot of a remote-controlled slope soarer would fly the aircraft, in that nose-down attitude is commanded when the aircraft is too far downstream and vice versa. Heading-angle command is limited to prevent the aircraft turning too far crosswind. Pitch-angle command is limited to prevent stall. All controller gains were initially tuned using 6-DoF simulations (largely via trial-and-error) and remained constant throughout the tests, with the exception of the inner-loop proportional gains, which were retuned whenever the oncoming wind speed changed significantly. In a fully autonomous implementation, these inner-loop gains could be scheduled using the assumed knowledge of the wind speed.

5.3. Desired controller behaviour
Ideally, upon entering the updraft, the aircraft should be positioned by the navigation and guidance systems somewhere along the target trajectory, with a horizontal velocity component close to zero, before the soaring-mode controller is activated. Here this was done using manual control of the pitch- and roll-angle
set points (i.e. flying the aircraft in attitude-hold mode). As mentioned previously, fully autonomous control was confined to the phase in which the aircraft sits in the updraft and gains height. In some cases the soaring mode was activated at launch, and the aircraft was launched from within the feasible soaring region of the updraft. There is some margin for error in this initial placement. Depending on the precise details of the flow field, the control system will ‘capture’ the target trajectory if it is placed close enough to the trajectory (simulation results demonstrating this capturing behaviour are presented in section 6.1). Being initially upstream of the target trajectory is preferable to being downstream, because in the former circumstance the outer control loop will then command a nose-up attitude in order to move downstream, resulting in a greater height gain. Conversely, if the aircraft is too far downstream, the outer loop will command a nose-down attitude and the aircraft may lose height to the point where it is outside of the feasible soaring region (or hits the ground). The latter problem could be circumvented by a (slightly) more complex control law involving initially maintaining horizontal position until sufficient height is gained such that either the target trajectory is intercepted or the aircraft has sufficient height to move forward to intercept the target trajectory. Alternatively, if sufficient processing power is available, an optimal trajectory from an arbitrary starting point may be calculated using the aerodynamic model and an optimisation algorithm.

Another limitation of this basic controller is that if the wind speed is lower than expected, the MAV may find itself moving upstream relative to the ground even when the commanded pitch angle is at its maximum. Human pilots of remote-controlled slope soarers typically alleviate this problem by performing a series of turns from side-to-side to prevent the aircraft from moving too far upstream. There is no allowance for such manoeuvres in the control system developed here, instead it was assumed that the aircraft mass is low enough for this not to happen. The next evolution of the controller will endeavour to replicate this strategy. The simplistic way in which the desired trajectory was calculated makes it easy to compute in real-time on-board the aircraft. Again, it should be emphasised that this quasi-steady approach will not yield the exact optimal trajectory, nor can it optimise the trajectory from an arbitrary starting point. This can only be done with an optimisation algorithm.

6. Results

6.1. Simulations
The aerospace blockset of simulink (Mathworks, Inc.) was used to perform simulations using the 6-DoF model. The simulations were used to analyse glide performance, verify the control-system architecture, determine the response of the system to disturbances, and tune the control-system gains.

Selected simulation results are shown here to demonstrate the behaviour of the idealised control system. Sensor and state-estimation errors were not modelled, while control-effector responses were modelled as first-order lags (\( \tau = 0.05 \text{s} \)). Tuning of gains using simulation results was done mainly by trial-and-error, and the resulting gains were a compromise between reducing overshoot when the control law is activated with the aircraft not exactly on the desired trajectory and rejection of disturbances caused by turbulence.

Figure 13 shows simulated flight paths, along with the desired trajectory, for the potential-flow velocity field computed for Johns hill with an incoming wind speed of \( V_0 = 8 \text{ m s}^{-1} \). Results for various starting positions, heights, and velocities relative to the ground \( (V_g) \) are shown. In all cases, the controller effectively captures the target trajectory. As expected, when the MAV starts downstream of the target trajectory, some height is lost initially. Some lateral overshoot is also noticeable when the initial position is offset from the desired trajectory in the cross-wind direction. In figure 13, this is particularly visible for the trajectory computed from a start point 30 m downstream of the target trajectory.

To examine the effect of turbulence, the mean wind velocity was set to a constant value throughout the entire volume, and the aircraft was commanded to track a straight vertical trajectory from its starting point. Turbulence was incorporated into the simulation by use of the von Karman wind turbulence model block in simulink, which generates random velocity and equivalent angular-rate time histories according to the empirical spectra given by von Karman (1948). The model also takes into account proximity to the ground in that the vertical turbulence intensity \( (I_v) \) and length scale decrease relative to the horizontal values \( (I_h \) and \( I_l \) ) with decreasing distance to the ground. It has been shown that these spectra are consistent with turbulence observed in urban environments (Thompson 2012).

Figure 14 shows the results of the simulations for various turbulence intensities. The horizontal and vertical turbulence length scales were 180 and 40 m, respectively, for all cases shown. These values are larger than would be expected in highly built-up environments, but it can be argued that they create a more severe test of the system, as prolonged drops or increases in wind speed are the most likely to cause the controller to fail than are shorter transients. Indeed it can be seen in the plot of MAV height as a function of time (bottom-right of figure 14) that the deviations from the nominal climb rate can be significant and prolonged. Common to the two simulations in which turbulence intensity was greatest, was the fact that the average climb rate decreased, as significant energy was wasted in manoeuvres to correct the MAV’s position.
Also common to all turbulent-flow simulations, and visible in the vertical view provided in figure 14, is the fact that longitudinal deviations from the target trajectory were greater than the lateral ones. This remained true despite attempts at further tuning the longitudinal control-loop gains. The standard deviations of the position errors for each of the turbulent-flow cases shown in figure 14 are summarised in table 3.

6.2. Flight tests

Initial flight tests were performed with the system tracking a pre-programmed, purely vertical trajectory. In subsequent tests, the target trajectory was calculated using the method discussed previously. In all cases, only planar trajectories were considered because the full 3D velocity field was not available. For the Johns hill tests, the plane considered was the vertical plane running perpendicular to the hill crest (i.e. that shown in figure 4). For the building 201 tests, the plane considered was the vertical plane coinciding with the building centreline (i.e. that shown in figure 1). The accuracy estimate produced by the GPS unit was also logged. Typical accuracy for the Johns Hill site was reported as ±0.7 m in the horizontal direction and ±1.1 m in the vertical direction. For the building 201 site the GPS accuracy was worse, presumably due to interference and multi-path effects; typical accuracy here was reported as ±1.5 m in the horizontal direction and ±2 m in the vertical direction.

6.3. Flight test one—Johns hill

An example flight path for an initial test at Johns Hill is shown in figure 15. In this case the system was tracking a vertical trajectory, and the soaring-mode controller was activated at launch time. The origin of the coordinate system is the launch point, which was approximately 30 m upstream of the hill’s crest. In this case, the wind was approaching from a heading of 355° (as determined by the average heading of the aircraft during the flight); this meant the wind was blowing slightly across the hill, as the nominal wind bearing (i.e. that which blows straight up the hill) is 020°. A reference wind speed of 7.5 m s⁻¹ was obtained from the average wind speed measured by a nearby weather station. It was used as the upstream velocity in the potential-flow model. It can be seen that most of the height gain for the MAV occurred in the first 2 min (120 s) of the flight, after which the aircraft hovered around the ceiling height. The peak height gain was 110 m (361 ft). The horizontal position relative to the

![Figure 13. Simulation results for capture of target trajectory from various starting locations and velocities, for Johns hill potential flow field (no turbulence), $V_0 = 8 \text{ m s}^{-1}$; target trajectory shown as thick grey line. Note that crest of hill is located at $N \approx 340 \text{ m}$ (the North-coordinate here corresponds to the x-coordinate in figure 11).](image-url)
target soaring trajectory was maintained reasonably well, with the standard deviation of the position error being 3.05 m. With the exception of a few large lateral deviations, the flight data exhibit the same trend predicted by the turbulent simulations, in that longitudinal deviations are on average larger than lateral ones. For this flight, the standard deviation of the longitudinal position error was 4.29 m, while that of the lateral position error was 2.49 m.

### 6.4. Flight test two—Johns hill

Tracking a calculated trajectory at Johns Hill was attempted in a subsequent test (on a different day with different wind conditions, in which \( V_0 \approx 6.5 \text{ m s}^{-1} \)). The results of this test are shown in figure 16, where separate north- and east-facing views are shown to better illustrate the trajectory. The initial part of the trajectory has the MAV moving slightly upstream as height increases, followed by a subsequent move downstream. The desired trajectory was tracked reasonably well, although again the longitudinal position error was noticeably larger than the lateral error (the wind direction was 340° in this case, so the longitudinal position can be judged fairly accurately from the north coordinate, and the same is so for the lateral position and the east coordinate). However, the MAV did not gain sufficient height to reach the downstream-moving part of the desired trajectory (i.e. where the trajectory would take the aircraft uphill). The calculation predicted a ceiling of 130 m (427 ft), but a height of only 80 m (262 ft) was reached. This is not surprising, given the fact that the potential-flow model is not expected to be precise and would likely over-predict the wind velocities because friction is neglected. Also, the wind in this case was 40° from the nominal direction, reducing the magnitude of the updraft. Furthermore, the aerodynamic model was based on the unmodified MAV, while the glide performance of the MAV would have been substantially adversely affected by the addition of the carbon fibre straps and damage sustained in several earlier landings.
6.5. Flight tests three and four—building 201

Soaring at the building 201 site proved very difficult, for reasons which will be explained in section 7. Trajectory data for two flights are shown in figures 17 and 18. On the day of the flight test, the average wind speed at a height of 10 m was 10.5 m s\(^{-1}\), as measured by a nearby ground-based weather station. The MAV was launched from the upwind edge of the roof, and the flights ended with the MAV either being flown manually onto the roof or to the ground. Attempts to activate the soaring-mode controller at launch time were not successful, so the MAV was initially flown in attitude-hold mode and the soaring mode was activated once its flight was stabilised. A simple vertical trajectory was used after it was discovered how much difficulty the control system (and human pilots) encountered in holding position.

For the flight shown in figure 17, it can be seen that the human pilot was able to maintain flight for close to 30 s, but without significant height gain. When the soaring-mode controller was activated, the autopilot was initially able to hold altitude for about 10 s, but the aircraft was slowly moving upwind as it did so. To correct this, the autopilot commanded a nose-up attitude, resulting in some height gain and the aircraft moving back toward the building. Shortly after, the aircraft appeared to enter a stall and descend rapidly. Manual control was resumed, and the human pilot kept the aircraft aloft for another 20 s (again struggling with vertical and lateral control), before a very strong gust of wind blew the aircraft over the roof, and the pilot was forced to land the aircraft on the roof.

For the flight shown in figure 18, the human pilot was able to gain height from launch, although lateral control was difficult as evidenced by the movement parallel to the building face. Vertical control was also difficult as can be seen in the height profile. As a result, it was necessary to activate the soaring-mode controller when the aircraft was not fully stabilised. The aircraft was moving backward (toward the building) at this time, and it appears that the autopilot overreacted by commanding a large nose-down movement, causing the aircraft to move forward and lose a significant amount of height. Manual control was resumed, and the human pilot kept the aircraft aloft for another 20 s (again struggling with vertical and lateral control), before a very strong gust of wind blew the aircraft over the roof, and the pilot was forced to land the aircraft on the roof.

7. Discussion

Flights at Johns hill were consistently successful, with the simple controller able to maintain wind-hovering flight for as long as the onboard batteries would last (the longest flight was about 15 min, and was only terminated to minimise the risk of battery exhaustion, as there was no on-board battery monitor). In contrast, the maximum duration of autonomous soaring flight at building 201 was just under 20 s.

For the first flight at building 201 (figure 17), the observers noticed a prolonged drop in the wind speed during the time in which the soaring-mode controller was active. This is believed to be the reason for the aircraft initially moving forward, and then stalling when attempting to move back toward the building. While significant lateral deviation is noticed in the latter part
of the autonomous portion of this flight, it is believed that this was a result of the stall, and not the reason for the height loss. Nevertheless, this would have exacerbated the height loss, because the lateral movement would have caused the aircraft to move further from the strongest updraft area. For the second flight at building 201 (figure 18), longitudinal movement was also the problem. Large-scale gustiness prevented the aircraft from ever being stabilised in pitch, and the soaring-mode controller was activated under an accelerated flight condition from which it could not recover. Very strong gusts eventually caused the aircraft to be blown backward uncontrollably, onto the leeward side of the building 201 roof, even under manual control.

At the beginning of this work, it was hypothesised that short-scale, high-frequency turbulence would be the biggest barrier to maintaining control in an urban soaring environment. The results from flight testing indicate the opposite—low-frequency gusts (i.e. those of 10 s duration) posed the most significant challenge to autonomous, unpowered wind-hovering. This was evident in the results obtained at the building 201 site: on the day of testing at that site, nearby weather stations measured gusts of approximately twice the mean wind speed. The simple linear controller, while appropriate for small perturbations of the MAV’s position and oncoming wind speed, could not respond appropriately to these prolonged periods of deviation from the nominal wind speed. This is not entirely due to deficiencies of the controller, as the aerodynamic properties of the MAV also limit its ability to maintain height when the wind speed deviates significantly from the optimal glide speed of the MAV. For example, in the first building 201 flight, if the stall had been prevented by lowering the nose, the aircraft would have moved too far upstream and out of the updraft area.

A human pilot was able maintain flight in front of building 201 for longer than the autonomous controller could because he could observe when the wind speed changed and sacrifice the holding of the desired horizontal position to keep the MAV in the air. However, even with a human pilot flying the MAV in attitude-hold mode to assist in dealing with high-frequency perturbations, the maximum flight duration was still only about 60 s (with the average being about 30 s). Of course this depends on the skill of the pilot, but it is evidence that even with an improved control system, prolonged autonomous flight in gusty conditions would be difficult. Inevitably some power must be input if flight is to be sustained, much like kestrels must begin to flap their wings when the wind speed is insufficient to maintain wind-hovering flight.

8. Conclusions

The aim of this study was to examine the feasibility of autonomous orographic soaring for a fixed-wing MAV in an urban environment using a strategy employed by kestrels, known as wind-hovering. Kestrels use wind-hovering to maintain a constant position of their head with respect to the ground, which helps them to detect movement on the ground when hunting for prey. The authors believe this to be a useful strategy for fixed-wing MAVs, both to assist in conserving power by staying within a confined
orographic updraft, and to provide a stable platform for surveillance.

In terms of autonomous flight duration, flight tests at an ideal site for soaring (Johns hill) were successful, while tests in front of a building (building 201) were less so. The fact that limited success was achieved using only a basic platform and control algorithm suggests, but does not prove, that the concept of urban orographic soaring is feasible. The extremely gusty nature of the wind on the day of testing at building 201, combined with the building’s geometry, mean that these were perhaps some of the most difficult conditions under which to perform orographic soaring.

Figure 17. Trajectory for flight test at building 201; target trajectory shown in red, autonomous track shown in blue, non-autonomous shown in green.

Figure 18. Trajectory for flight test at building 201; target trajectory shown in red, autonomous track shown in blue, non-autonomous shown in green.
The greatest difficulties experienced at the building 201 site were strong gusts of relatively long duration (~10 s). These prolonged changes in wind speed rendered the linear control system ineffective. This effect was also noticeable at Johns hill, where the control system could not hold the MAV’s longitudinal position as well as it could hold the lateral position, but the gusts were not strong enough to cause the MAV to move outside the area in which the updraft was strong enough to soar. This was also aided by the fact that the extent of the updraft area at Johns hill was an order of magnitude greater than that at building 201, which highlights the need for accurate control (both longitudinal and lateral) when soaring in localised updrafts in urban environments.

9. Future work

The northerly aspect of building 201 was chosen because it is free of obstacles immediately upstream that would likely cause short-scale, high-frequency turbulence. This kind of turbulence was initially hypothesised to present the most significant challenge. Future testing will explore soaring from a different side, as northerly winds in this area are always associated with large-scale gustiness due to a mountain range approximately 40 km north of the building. Testing in winds from a different direction would likely increase the level of high-frequency turbulence present, but at no stage did the control system appear to struggle with high-frequency perturbations. Performing wind-field measurements concurrently with future flight tests may also help to determine whether any shortcomings are due to aerodynamic limitations, or controller limitations.

To maintain control in gusty winds, a more advanced control system is necessary. Such a system must take input from airspeed sensors to determine when it is necessary to sacrifice the holding of the nominal position in favour of keeping the MAV aloft. But even if this is done, depending upon the nature of the wind gusts, the MAV may not be aerodynamically capable of staying aloft without power. In a MAV equipped with a motor, the system could increase propulsive power to assist when soaring performance is inadequate.

In addition to these controller improvements, estimation and actuation components could be easily improved over the basic implementation demonstrated here. A barometric-altitude sensor or vision-based position sensing would help with state estimation and could also be used to directly augment the control system. Although the results showed that lateral position was held more accurately than longitudinal position, a rudder- and yaw-damping loop would further assist in maintaining position by enabling more direct control over the aircraft’s heading.

If the challenges encountered here can be overcome, then the next step toward autonomous urban soaring lies in building maps of urban areas, and path planning between updraft areas. It is envisaged that in a real-world application, this system will contain a flow-field map of various primitive geometric shapes for different relative wind directions, which when combined with a map and real-time mean wind-speed data, will permit an inexpensive estimation of soaring locations and trajectories. Large cities with tall, slender buildings present a greater challenge to urban soaring, as the majority of the approaching airflow passes around the sides of these buildings, and the updraft region is confined to a relatively small area near the top. Areas containing buildings of low aspect ratio are more desirable, and these are more likely to be found outside of city centres. A study of the updraft flows in extended built-up areas (as opposed to single structures in isolation) has been commenced (Leung et al. 2015).

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