UAV RIDGE SOARING IN AN UNKNOWN ENVIRONMENT

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Abstract

This paper describes a simulation environment and an initial investigation of a method of providing turn advice to an Unmanned Air Vehicle in an attempt to make use of air rising over ridge-lines or other rising ground in the terrain. The exact form of the terrain is unknown to the adviser. The aim of providing this advice is to increase the time aloft.

Biography

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Introduction

The aim of this project was to enable an unmanned aerial vehicle UAV to increase the amount of time it spends aloft by taking advantage of any lift or rising air that occurs naturally due to the terrain – in particular, ridge-lift, which is formed when wind is deflected upwards by rising ground. Many of us have observed sea birds gliding for long distances along coastal dunes or cliffs. In the same manner UAVs may conserve their energy by making use of ridge and other lift including thermals to greatly extend their endurance. The use of ridge-lift is important to extending the endurance of UAVs in important littoral applications. Mission planning software may to choose to vary the initial mission plan in real-time to remain aloft through the use of environmental energy sources.

This paper presents an initial study into the feasibility of a guidance sub-system (Adviser) that with no prior knowledge of the wind conditions or elevation model of the terrain could provide turn advice to the auto-pilot, which would make best use of available ridge-lift. To achieve this the guidance sub-system receives information from the UAV's onboard instrumentation – GPS, altimeter and airspeed – and over time builds a map of the airflow conditions (lift and wind direction). The information is stored and retrieved using the GPS location as the index and takes account of GPS and UAV manouvering limitations.

Research Aircraft

The Aerobotics Group at Monash operates a number of medium endurance (~2hr) electrically powered research UAVs in the 2-5kg class with payloads to 1.5kg (Figure 1, Table 1). These endurances are without recourse to use of ridge lift however the power required to maintain this aircraft with full payload in cruising flight at 54km/hr is approximately 28w. While our research aircraft were not used directly in this study it is known that under manual control they can make effective use of ridge lift.

Ridge Lift

Three-dimensional models of the behaviour of air as it flows over a ridge are complex and even more so if turbulence[4] is considered. Generally however the direction of airflow at a location depends on:

- wind velocity;
- static stability of the air;
- terrain shape.

Time is also involved as the first two of the above parameters are not constant (it could be argued the third is also not constant).

Figure 2 [5] shows possible paths taken as air travels over a ridge. It can be readily seen that apart from the direct effect of rising ground (ridge-lift) there can be an influence extending to quite high altitudes (wave-lift). The paper concerns itself with direct ridge-lift although the techniques described are applicable to lift at all altitudes.

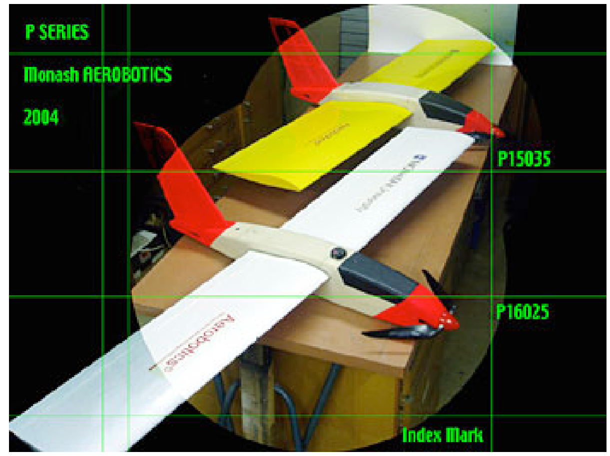

Figure 1: The P Series Aircraft.

TABLE 1
SPECIFICATIONS OF AIRCRAFT P16025

Span	160 cm	**Motor**	B4021L 5:1 13x11
Chord	25 cm	**Duration**	60-90 minutes
Length	106 cm	**Speed**	30-135 km/hr
Controls	Elevon	**Battery**	24x1200mAH LiP
Weight	2.2 to 3.2 kg	**Autopilot**	Non-inertial

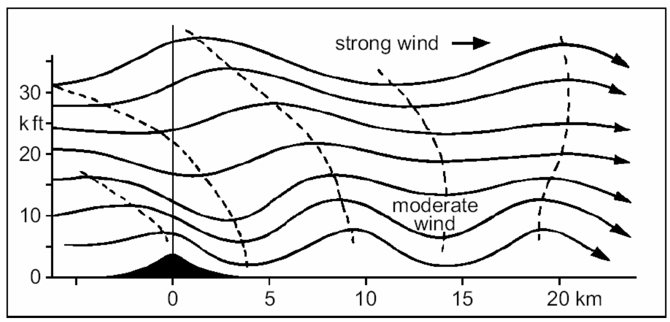

Figure 2: Typical ridge and wave lift (reproduced from [5])

Simplified model of ridge Lift

For this initial study the following simplifications were made:

- at a certain elevation above a ridge, the effect of the ridge becomes negligible. The elevation at which this occurs is termed the "neutral elevation".
- the static velocity of the wind is constant with respect to altitude. In actual fact, air travels more slowly along the ground than above it.

Figure 3 shows the cross-sectional view of the proposed ridge. It can be seen how the ridge deflects the air at lower altitudes most severely, whilst the air nearer the neutral elevation is less affected.

From the continuity equation (1) [6] the air speed will increase as the area through which it flows is decreased :

$$\Delta Volume = A_1 v_1 \Delta t = A_2 v_2 \Delta t = 0 \quad (1)$$
$$\therefore A_1 v_1 = A_2 v_2 .$$

This increase in air speed occurs as the on-slope wind encounters the ridge. The development of a vertical component to this airflow can be seen in to an exaggerated degree in Figure 3.

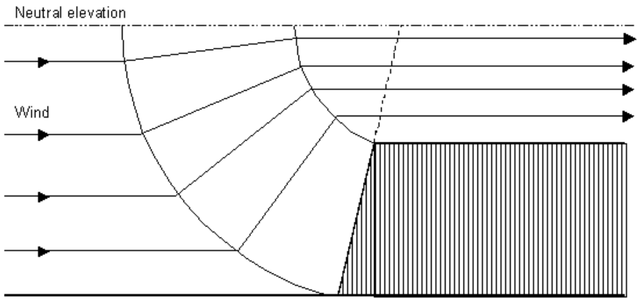

Figure 3: Simplified ridge lift model

It is assumed that the increase/decrease in airspeed is symmetrical on the upwind/downwind sides of the ridge is symmetrical. In practice the behaviour of the airflow downwind of a ridge not as simple for high wind speeds but it is a reasonable approximation for intermediate wind-speeds where turbulence is limited as is the case for the wind speeds used in our simulations.

Wind Model

The wind used for the simulation has been modelled as having a constant direction and a randomly varied speed. The average speed and the maximum percentage change is specified as part of the simulation. These parameters are set in the terrain description file.

Simulation environment

There are many public domain flight simulators including FlightGear [1] and the Slope Soaring Simulator (SSS) [2] which may be used for extensions to this research but for the initial study it was decided to implement a simple simulated environment within which to test the Adviser and its algorithms.

The Simulation System provides a stylised 3-dimensional image to allow the UAV to be observed [7]. The terrain of the simulated world is read in from a configuration file and generated dynamically. Moderately complex terrains may be generated by specifying several, possibly overlapping ridges, of different geometries in the configuration file. The program reads the configuration file and successively adds each ridge into the otherwise flat terrain. The use of a simple configuration file allows the terrain to be edited quickly.

Constraints

There are a number of limitations to available information and the practical constraints of fixed wing aircraft that must be considered.

Height above terrain

Many UAVs do not have radio altimeters or other means to measure altitude above the ground. Almost all UAVs have density altitude or GPS altitude. UAVs may have a limited digital elevation model (DEM) available to them giving height above ground at the current GPS coordinates. For this work no knowledge of the terrain is assumed from which potential ridge lift may be inferred.

GPS acquisition delay

Readily available GPS units provide coordinate updates every second. There is a further computational and transmission delay in these updates leading to an overall update lag of around 1.5s. Our UAVs cruise at approximately 20m/s leading to a position error of up to 30m along with several degrees of error in aircraft heading.

Wind-speed

Wind-speed is not directly available to the aircraft but may be inferred over time from airspeed and GPS groundspeed which itself may be directly measured.

Pitch and roll

The attitude of the aircraft, that is its roll and pitch (nose up or down) angles, is available directly.

Manoeuvring ability

Fixed wing aircraft have manoeuvering constraints including maximum turn and climb/descend rates.

The adviser

In order to give advice, the adviser uses current and prior data obtained from the UAV instrumentation. The interpretation of this data requires care as was previously discussed. The strategies adopted within the Turn Adviser draw from those typically used by experienced human pilots. This experience is considerable and is not yet encompassed within the Adviser.

Simple adviser

The first turn adviser, used to test the development of the simulation system, operated by simply using the roll of the UAV. When the UAV proceeding on a random course enters vertically moving air, the aircraft will typically roll away from the most rapidly rising air. The adviser detects this roll and advises the aircraft to turn into the lift; no account is taken of any pitch behaviour that may occur when the aircraft flies directly into or out of lift. Importantly, the simple adviser does not record and therefore reuse any information obtained from the UAV's instrumentation; it does not *learn.*

Advanced adviser

Unlike the initial simple adviser, the advanced adviser progressively maps the lift available to the UAV and as the map builds up is able to provide improving advice on which direction to turn. The Adviser may immediately provide advice with little or no information while progressively building its lift map. Not surprisingly this usually provides poor advice.

Pre-advice pattern flight

The purpose of instructing the UAV to fly a search pattern is to partially fill the Adviser's internal map of lift locations. This pre-advice pattern may be flown under power for our UAVs.

The path the UAV follows when flying the search pattern is a clockwise decreasing spiral. The search pattern starts by following the outside of the area covered by the internal map, and proceeds to spiral inwards with user-definable spacings between successive spirals. The spacing can be changed in the simulation configuration file.

Based upon the cruise speed of the UAV, and the radius of its turning circle at that speed, the algorithm calculates the area of sky adjacent to the UAV that cannot be reached (through inability to turn tightly enough). Because this region of sky cannot be reached, the algorithm does not test it.

The algorithm divides the space around it into 30° sections and accumulates the lift from each search path into its accompanying section. Once all the paths have been processed, the centre angle of the section with the greatest accumulated lift is decided to be the most optimal angle of travel. Should all the sections have an aggregate lift of zero, then the algorithm will determine the section with the most negative lift and advise that the UAV should turn *away* from that section. If there are no sections whatsoever with any kind of lift, positive or negative, the algorithm advises the UAV to continue upon its current heading.

The Adviser contains a "safety" option: should the UAV stray too far from the centre of the map, the turn adviser will instruct the UAV to head back towards the centre. The distance the UAV can travel from the centre is dubbed the Escape Distance, and is specified in the configuration file. It is usually set to a value large enough to allow the UAV to roam freely over the entire map but can be set to zero to disable it.

Data representation

The computational power available on the UAV is limited. Some attention was given to reducing the storage required for the Turn Adviser's data structures. Rather than store the map as a contiguous array, the rows are divided such that each row is an individual array. The map maintains pointers to these rows. The design choice was made in order to minimise the cost of moving the map, should the occasion arise. For example, if the locations the map covers are to be shifted vertically by one row, it is a simple operation to discard the out-of-range row, shift the pointers to the remaining rows and create a new row. The order of this procedure is $O(n)$ n being the number of locations. Had a contiguous array been used, it would be necessary to move every element of every row to its new position explicitly. The order of doing this is $O(n^2)$, a much more severe penalty. It is noted that horizontal moves still attract a cost of $O(n^2)$. Using a linked-list could reduce this; however this improvement must be balanced against the added complexity of element traversal. It was decided that there would be no benefit in using a linked-list map.

The information each element of the map holds is stored in a structure containing two fields: a field indicating whether the information is valid, and a field indicating the amount of lift at this point.

Experiments

The same terrain (Figure 4) was used for all experiments. The results were obtained using a 0.5s time step. The conditions were:

- The UAV starts from position (500m, 500m) and is heading north.
- The UAV is limited to fly within the altitudes of 750m and 1200m (this prevents the UAV from flying into the ridge or above the lift).
- The wind speed is 7m/s from 20° east of north.
- Results are averaged over three tests.

The metrics chosen to enable measurement and comparison are the:

- average amount of lift per unit time (m/s); and,
- fraction of time spent in lift.

Pre-advice pattern

The first test is to determine the benefit of using the initial pattern flight and to determine which grid width performed the best. All simulations used the following parameters those being the:

- map is located at (1500m, 1000m);
- map length is 1000m; and,
- distance between map elements is 20m.

The results of the tests are summarised in Table 2.

TABLE 2. Parameters and results of Test A.

Test	*Pattern Width (m)*	*Average lift / unit time (m/s)*	*Fraction of time in lift*
A1	Not Used	-0.24	0.14
A2	50	0.55	0.39
A3	100	0.56	0.38
A4	200	0.55	0.34
A5	300	0.49	0.25
A6	500	0.52	0.27
A7	700	0.36	0.18

It shows that using the pre-advice flight pattern provides a significant improvement to the quality of the advice the system can give. This is evidenced by the dramatic improvement in average lift per unit time. The results confirm the expectation that providing the advice system with initial information allows it to perform better.

Advice performance

The next test is to compare the performance of a UAV with the advice system against an unaided one.

First, the valueof the metrics for an unaided system are calculated. To do so, following assumptions and reasoning are used:

- The UAV is in an area with lift but the location of the lift is unknown; and,
- The UAV adopts a strategy of flying a fixed-location circle.

The chance of the UAV flying in lift will depend on how "lift rich" the area is. For a long, straight ridge such as a sand dune, there is positive lift only at the windward face so the area may be divided into three parts – two no-lift areas with a lift area in between. If the no-lift areas are twice as long as the lift areas, the fraction of time spent in lift will be ~0.20. This number will decrease as the lift section becomes thinner. In the best lift case for the given wind direction and speed, the vertical air velocity will be cosine(20°)*7 or 6.6m/s directly upward. In the worst case, the lift will be zero. Thus, the average vertical air velocity will be (6.6+0)/2 or 3.3m/s upward. The average amount of lift per unit time is therefore 3.3*0.2 or 0.66m/s.

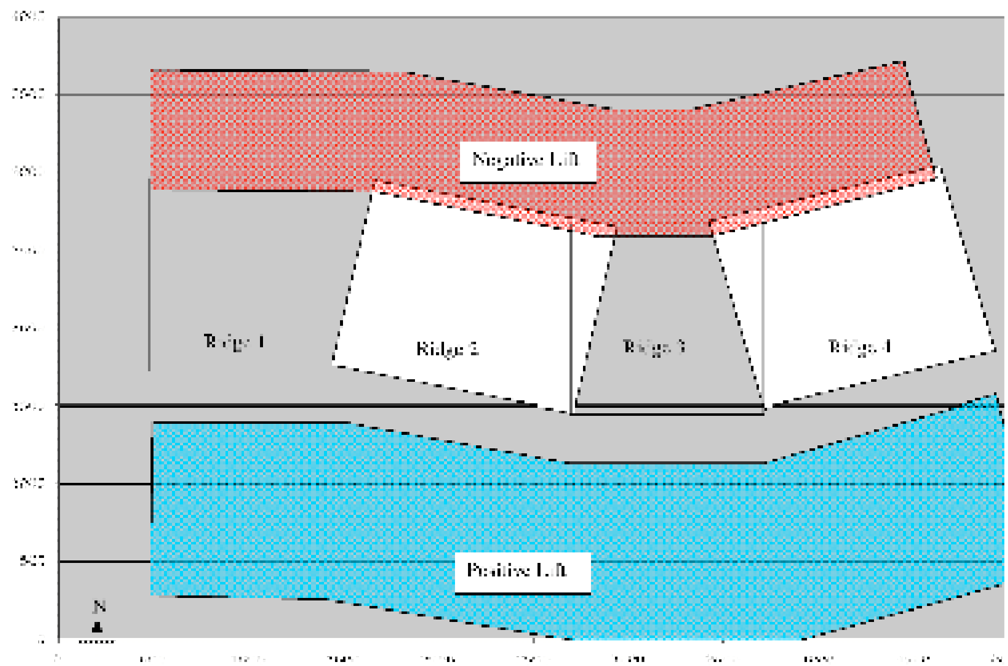

Figure 4: Ridge configuration

These figures are determined using ideal conditions. The completely vertical air will only be found at the very face of the ridge which is a very dangerous place to fly – a place the Adviser does not fly. As such, the unaided UAV's performance will be over-represented by these figures.

If instead a mountain-type ridge is used, there are two lift areas and two no-lift areas. One of the lift areas would be positive, the other negative. Thus, the fraction of time spent in lift would be ~0.5 and the average amount of lift per unit time would be ~0. If there is a plateau, the fraction of time spent in lift would decrease.

Table 3 shows the parameters used when performing test B. Table 4 shows the results of the test. The advice system is now considered against an unaided one.

TABLE 3. Parameters of Test B.

Test	*Map Position (M, M)*	*Map Length (m)*	*Map Sep. (m)*	*Pattern Width (m)*
B1		1000	20	
B2		1000	40	
B3	(1500, 1000)	1520	20	200
B4		1520	40	
B5		2000	40	
B6	(1500, 500)	1000	20	Not used
B7				200

Tests B1 through B5 are testing the system for a variety of map length and elements separations to see how they compared. The results show that the change in separation from 20m to 40m made little difference to the fraction of time spent in lift. The change in map size, however, did have an effect. The smaller map size has a larger average lift. This may be due to the larger map covering more area and causing the UAV to travel in negative lift areas when flying the Pre-advice Pattern. Additional tests B6 & B7 were conducted in a more lift-rich area. These confirm that the performance of the UAV is improved significantly by using the Pre-advice pattern.

TABLE 4. Results of test B – the performance of aided and unaided UAVs.

System	*Test*	*Average lift / unit time (m/s)*	*Fraction of time in lift (s/s)*
Unaided			
	Sand Dune-type	~0.66	~0.20
	Mountain-type	~0.0	~0.50
	Average (if types equally likely)	~0.33	~0.35
Aided			
	B1	0.53	0.32
	B2	0.53	0.32
	B3	0.36	0.22
	B4	0.39	0.24
	B5	0.14	0.29
	Average	0.39	0.28

B6	0.67	0.19
B7	0.53	0.34
Average	0.60	0.27
Aided Average	0.50	0.28

Results

Overall, the advice system performs slightly better in the average lift per unit time and slightly worse in the fraction of time spent in lift compared to a UAV simply orbiting in a circular path over the ridge.

For the Advisor the average performance was:

Average lift per unit time: 0.5 m/s
Fraction of time spent in lift: 0.28

This can be compared against an unaided system:

Average lift per unit time: 0.33 m/s
Fraction of time spent in lift: 0.35

Whilst the UAV tended to find high lift areas it was not able to stay in those areas with the current manoeuvering strategy. It can also be seen that the fraction of time spent in lift decreases as the pattern width decreases. The smaller the pattern width, the longer it takes the UAV to populate the map. It is possible to interpolate values in the map so that at least some advice can be given.

The initial search pattern greatly improved the performance of the Adviser with an approximately twofold increase in the amount of time the UAV spent in lift and a threefold increase in the average lift per unit time. Map grids of 50, 100 and 200m performed similarly, though the best was 100m.
The assumed wind-speed of 7m/s is at the lower bound of what would be usable flying conditions. For context the nominal sink-rate in still air for a typical 2M wingspan model glider in still air is ~0.7m/s while for our UAVs it is ~1m/s. Normally available lift scales with increased wind-speed.

Conclusion

The research has shown that it is feasible to exploit ridge-lift using normal UAV instrumentation. An initial discovery search pattern is essential if acceptable performance is to be obtained. Improvements are required to manouvering strategies so that the UAV may stay in discovered lift for a greater fraction of the time.

Coastal ridge soaring is applicable to important littoral applications of UAVs. The lift-mapping scheme incorporated into the Advisor readily extends to exploiting other forms of lift including thermals for more general cross–country flight, where there is usually considerably flexibility as to which route to take to reach some goal. Techniques for full size gliders well known to the soaring community may also be brought to bear within a real-time mission planner for cross-country flight.

Elements of the research presented here have been integrated into our autopilot [8]. Early practical results are very promising permitting significant extensions of flight time particularly for electrically powered aircraft.

Acknowledgments

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