Utilization of Wind Energy in Optimal Guidance Strategies VIDA Real-Time Nonlinear Control Methodologies

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In this paper, a real-time, on-board methodology to utilize wind energy associated with air currents is proposed for saving power, minimizing fuel consumption and increasing endurance during ight of an unmanned aerial vehicle (UAV). The UAV is modeled as a 3D dynamic point mass and a non-linear receding horizon control algorithm is investigated for implementation of real-time guidance strategies developed for wind energy utilization.

Nomenclature

AR aspect ratio
C_D drag coe cient
C_{D_0} zero-lift drag coe cient
C_L lift coe cient
D aerodynamic drag
e Oswald e ciency factor
h inertial altitude
J performance index K
induced drag factor L
aerodynamic lift m
aircraft mass
n g-load factor
P power
S wing reference area
T thrust
t time
V airspeed
$W_{x;y}$ wind components (East, North)
W_h wind component (Upwards)
x; y position vectors (East, North)
free-stream-relative ight path angle
bank angle
heading angle measured clockwise from the
North air density
normalized time
$(\ )_0$ initial value
$(\ )_f$ nal value
$(\ )^r$ reference value
( ) optimal control value

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$(\dot{\ })$ time derivative

$(\ )'$ derivative w.r.t. normalized time

I. Introduction

In 1903, the Wright brothers demonstrated powered aircraft ight for the rst time in history. In a little over a hundred years from that date, mankind has gone from ying primitive wooden aircraft a few hundred feet at a time to sending ying metal marvels across the planet.

While there are many examples of aircraft that have grown in size and scope over history, there are also examples of aircraft that have been scaled down in size but still maintain a massive scope: unmanned aerial vehicles. Small-scale unmanned aerial vehicles (UAVs) exist in a variety of forms and are used to ful ll a multitude of needs. A glider that a pilot controls remotely, a drone the military uses for surveillance are just two examples of the roles UAVs take and the needs they ll. Moreover, UAVs are used in applications for search and rescue, science, leisure, training, surveillance, agriculture, military, re- ghting, policing and more.

In order to serve these applications as best as possible, the aircraft we create are usually optimized with respect to a desired performance objective. They have gone from composition of wood to metal and from metal to composite. They have been revised and redesigned based on advancements in theory and empirical data. Such advancements include winglets, which enhance aerodynamic e ciency and save fuel by reducing the downwash induced on the wing. Their recent implementation on commercial airliners is evidence that aircraft innovations are not at an end. An observation worth noting is that the ways in which aircraft have improved over the years are mostly due to advancements in technology and supporting theory and the changes manifest in ways that are mostly physical (e.g. appearance, structure, and composition).

A less investigated approach to improving aircraft is to ask how we may bene t from changing the way we approach ight itself, as opposed to changing the object that ies. Nature commonly serves as an example of what works in our world. Inventors, entrepreneurs, enthusiasts, and more have looked to nature for ideas or in uence, and biomimicry has made an appearance in aviation. The prime example of ight in nature is the bird. Birds, like humans, seek e ciency. As a result, they take advantage of air currents (i.e winds) to reduce the e ort required to y. Birds have been observed taking advantage of air currents like updrafts, thermals, microbursts, and the e ects of wind shear. Before the onset of small aerial vehicles, taking advantage of the same air currents birds bene t from was not feasible with the size, speed, and overall scale of the aircraft available. With aircraft that have similarly low-mass and small-scale features to birds, near instantaneous changes in direction become practical. The possibility to take advantage of wind energy exists and simply needs a method of implementation for aircraft.

Modern day aircraft are on the verge of a major transformation. Autopilot technology has existed since the early 1900s. The advancements made to aircraft control systems, however, are as drastic as the changes to the aircraft themselves. Up until recent history, all aircraft have had a human pilot, regardless of any autopilot implementation. This precedent is nearing its end, with the onset of sophisticated autonomous control systems that enable aircraft to y a pre-determined human-selected course without any human interaction.

The transition to primarily computer-controlled aircraft is here and applicable in nowadays. With autonomous technology for UAVs already commercially available, the next steps are in two directions: widespread implementation and improvements. The improvements of interest for this research include the application of biomimicry in ight patterns to UAV guidance algorithms.

A. Background

The studies of ight in nature and improvements to aircraft cross paths from time to time and sometimes, evolutionary progress is made in the way we approach ight. Certainly, the observation of birds in ight spurred the inspiration for the Wright brothers to tackle the dream of human ight. While the rst aircraft to y had a set of xed unmoving wings, aircraft with wings that ap like a bird have been proposed and studied throughout history. None have come to be as successful as their xed wing counterparts but progress continues. In 2010, the Snowbird of the Human-Powered Ornithopter (HPO) Project at the University of Toronto o cially became the world's rst human-powered ornithopter.[1] The aircraft demonstrated the ability to climb in altitude and maintain level ight with apping wings as the only means of propulsion. Another way in which nature has in uenced our understanding of and approach to ight is through tubercles, the bumps on the ns of Humpback whales. Research has found that tubercles act as vortex generators to produce turbulent ow over the whale's n and improve stall performance.[2] Tubercles have been tested for applications in air with results indicating enhancement to lift properties.[3, 4] These examples of biomimcry hardly scratch the surface of the potential improvements we can harness from copying nature's approach to ight.

The ways nature approaches ight and the ways in which we might be able to bene t from a similar approach have been investigated in the past. Richardson[5] created a simple dynamical model of wind-shear soaring and found that an estimated 80-90% of the total energy required for sustained ight can be extracted from wind-shear soaring. The promise of energy bene ts from dynamic soaring motivated other research on the topic. Zhao[6] formulated a glider's dynamic soaring as a 3D point mass with utilization of wind gradients as a non-linear optimal control problem and investigated various performance indices and terminal conditions to yield di ering optimal ight patterns, each with their own prospective uses. Furthermore, using a 3D point mass and linear wind gradients, optimal powered dynamic soaring ights of UAVs utilizing wind gradients at low altitudes for reducing fuel consumption were studied by Qi and Zhao.[7] They were able to compare the characteristics of minimum thrust dynamic soaring cases with those of minimum power dynamic soaring to nd similar fuel savings bene ts between the two approaches. Additional air current research of Qi and Zhao[8] includes modeling a 2D point mass model of a UAV ying through a region of vertically owing thermal air current. Their results suggest signi cant improvements in UAV fuel consumption are possible by taking advantage of thermal air energy. Enforcing the e ectiveness of using thermal air currents, Akhtar et al.[9] created a positioning algorithm for autonomous thermal soaring where a simulated 6DOF model is used to estimate the interaction of a sailplane with thermal updrafts. In their study, a control system, based on classical theory, is used to guide the sailplane for maximum bene t from the thermal energy. A situationally unique approach to energy savings is taken by White, C. et al.,[10] who conducted a feasibility study for micro air vehicles (MAVs) saving energy by soaring near tall buildings. Provided issues of controllability could be overcome, the study ndings indicated the prospect for soaring to be realistic. The current status of the technology in the eld of miniature air vehicles and prospective future innovations were discussed by Gerdes et al.[11] in a review of miniature air vehicle designs with bird-inspired apping wings.

The utilization of these air currents and ight strategies requires computer algorithms capable of providing real-time guidance solutions. Recently, Gao, X.-Z., et al.[12] proposed a guidance strategy for dynamic soaring of UAVs that could reduce computational time to less than one percent of what is required by the Gauss pseudo-spectral method, thereby increasing the possibilities for an on-board real-time guidance strategy. Previous work by Ohtsuka and Fujii[13] proposed a real-time optimization technique for optimal state-feedback control of general non-linear systems. The technique utilizes the backward-sweep method to reduce the computational cost of the solution. In another study, Turkoglu,[14] generated an approach for optimizing ight trajectory to bene t from wind energy using real-time guidance strategies. When using the algorithm in a real-time simulation, a ve to ten percent decrease in total power consumption was observed.

The aforementioned advancements in our understanding of wind energy and software implementation methods will be the basis for this research.

B. Overview of the Research

The objective of this research is to investigate mathematical methodologies for achieving on-board implementation and function of real-time optimal guidance strategies in presence of wind. The optimal guidance strategies of focus for this research are those which utilize instantaneous wind information and adjust tra-jectory for e ciency accordingly. This requires the examination of not only computationally e cient and robust, but also on-board applicable, real-time optimization methods. An algorithm of nonlinear receding horizon control, proposed by Ohtsuka and Fujii,[13] is of main interest and will be implemented for the ap-plication of the real-time guidance strategies in presence of wind. The aim is to minimize fuel consumption and extend ight time bene ting from the wind conditions.

II. Aircraft System Description

Properly de ning the system at hand is critical to generating the parameters, equations, and algorithm so that the nal results can emulate reality to the desired level of accuracy. The typical approach to modeling the aircraft dynamics include de nition of a system with six degrees of freedom (6DOF). While this is common and serves as an accurate model, the computational burden induced by the highly complex system model is not ideal for real-time optimization applications. Furthermore, the accuracy required by the problem at hand can be achieved with an approach that boasts simplicity over the 6DOF system. For this research the aircraft is modeled as a three-dimensional (3D) dynamic point-mass with all the necessary ight trajectory parameters for trajectory analysis and optimization.

A. Equations of Motion

In de ning the aircraft as a 3D dynamic point mass, the equations of motion are:[14]

$$\bar{V} = (T \quad D)=m \;\; g \sin \quad \bar{W}_V \tag{1}$$

$$V \cos \; \bar{} = L \sin \; =m \;\; \bar{W} \tag{2}$$

$$V \bar{} = L \cos \; =m \;\; g \cos \; + \bar{W} \tag{3}$$

$$\dot{x} = V \cos \; \sin \; + W_x \tag{4}$$

$$\dot{y} = V \cos \; \cos \; + W_y \tag{5}$$

$$\bar{h} = V \sin \; + W_h \tag{6}$$

where

$$\bar{W}_V = \bar{W}_x \cos \; \sin \; + \bar{W}_y \cos \; \cos \; + \bar{W}_h \sin$$

$$W \; = \bar{W}_x \cos W_y \sin$$

$$\bar{W} \; = \bar{W}_x \sin \quad \sin \quad + W_y \sin \quad \cos \quad W_h \cos \tag{7}$$

For these equations, the terms to be used as inputs are thrust T , lift L, and bank angle . The states to be controlled are: the airspeed V , heading angle , ight path angle , and the coordinates $(x; y; h)$ of the aircraft relative to the inertial coordinate system location.

For this research, the UAV is assumed to be propeller-driven by an electric motor with a known power output and the UAV's mass m is assumed to remain constant over time. Given these assumptions, the thrust T , power P , and velocity V of the aircraft can be related as shown below.

$$T = P=V \tag{8}$$

The lift L and drag D forces experienced by the aircraft can be de ned as

$$L = \frac{1}{2} V^2 S C_L; \qquad D = \frac{1}{2} V^2 S C_D \tag{9}$$

and the drag coe cient is modeled by the parabolic drag polar[15]

$$C_D = C_{D0} + K C_L^2 \tag{10}$$

The induced drag factor K can be determined from the Oswald e ciency factor-e and the wing aspect ratio-AR as

$$K = \frac{1}{eAR} \tag{11}$$

B. Motion Constraints

Since the aircraft has real limitations to its movement, constraints are applied to the system to better resemble realistic aircraft flight parameters. The bounded trajectory states are power P , velocity V , flight path angle , bank angle , and coefficient of lift C_L. The specified limitations are shown below.

$$V_{min} \quad V \quad V_{max}; \; |\;| \quad {}_{max}$$
$$C_{L_{min}} \quad C_L \quad C_{L_{max}}; \; 0 \quad P \quad P_{max}; \; |\;| \quad {}_{max} \tag{12}$$

To further improve realism, the g-loading of the aircraft is limited as well.

$$n = \frac{L}{W} = \frac{V^2 S C_L}{2W} \qquad) \quad n_{min}\left(\frac{S}{2W}\right) \quad V^2 C_L \quad n_{max}\left(\frac{S}{2W}\right) \tag{13}$$

The minimum allowable airspeed is set as the aircraft stall speed and the maximum airspeed is chosen to be the desired cruise speed.

$$V_{min} = \sqrt{\frac{2W}{S C_{L_{max}}}}; \quad V_{max} = \sqrt{\frac{2W}{S C_{L_{cr}}}} \tag{14}$$

where $C_{L_{cr}}$ is the coefficient of lift required for steady level flight at the cruise velocity.

III. Problem Definition

The main effort of this research is to make a reduction in power consumption possible through use of wind energy via in-situ, on-board and instantaneous wind measurements. To do this, we will adopt a method for use of instantaneous, in-situ wind measurements to influence and optimize trajectory. The work of Turkoglu[14] focuses on development of such real-time, optimal trajectory guidance strategies based on gradient methods. This work builds on the previous work of Turkoglu[14] with a novel extension of applying the strategies with an advanced real-time optimization algorithm from the work of Ohtsuka and Fujii[13] (i.e. non-linear receding horizon control) that will serve for on-board, in-situ, real-time trajectory optimization routine.

A. Nonlinear Receding Horizon Control Based Real-Time Optimization Algorithm

The problem in hand is an optimal control problem, which is to be solved for a non-linear system in real time through minimizing the cost function over a receding time horizon. The corresponding form of the differential equation and the performance index for such a problem are shown below for convenience.

$$\frac{dx(t)}{dt} = f[x(t); u(t); p(t)]$$

$$J = \varphi[x(t+T); p(t+T)] + \int_t^{t+T} L[x(t'); u(t'); p(t')]dt' \tag{15}$$

Here, x(t) represents the state, u(t) represents the system input, and p(t) represents parameters that vary over time. With this problem setup, we seek an optimal control input and a resulting trajectory that will minimize the cost function, which is associated with minimum fuel consumption via the utilization of the wind energy. If we introduce a fictitious time axis , as defined by Ohtsuka,[16] where the present time t corresponds to = 0, then the aforementioned problem becomes a set of problems with a fixed horizon.

$$x \; = f[x(\;; t); u(\;; t); p(t + \;)]$$
$$x(0; t) = x(t) \tag{16}$$

The new problem set has the form of a typical optimal control problem where we formulate the Hamiltonian, which consists of the terminal cost function and the Lagrangian. It follows that the necessary condition for optimal control takes the form of the two-point boundary value problem shown in Eq.(17).

$$\begin{aligned} &x \;= H^T \;= f \qquad \text{where } x\,(0;\,t) = x(t) \\ &=\; H_x^T \qquad \text{where } \;(T;\,t) = '_x{}^T \\ &H_u \;= 0 \end{aligned} \tag{17}$$

In Eq.(17), represents the costate vector and H is the aforementioned Hamiltonian as de ned by

$$H = L + \;{}^T f \tag{18}$$

Based on this approach, the control methodology is obtained as

$$u(t) = \mathrm{arg}f H_u[x(t);\;(t);\,u(t);\,p(t)] = 0g \tag{19}$$

A backward sweep method is implemented, and the TPBVP is to be regarded as a nonlinear equation with respect to the costate at = 0 as

$$F\,(\;(t);\,x(t);\,T;\,t) = \;(T;\,t)\;\;'_x{}^T\,[x\,(T;\,t);\,p(t+T\,)] = 0: \tag{20}$$

In order to reduce the error associated with the integration, a stabilized continuation method is used as follows:

$$\frac{dF}{dt} = A_s F \tag{21}$$

where A_s denotes a stable matrix to make the solution converge to zero.

Here, a linear di erential equation is produced based on the previous equations:

$$\frac{@}{@} \begin{bmatrix} t \\ x_t \;\; x \end{bmatrix} = \begin{bmatrix} & C \\ A & B \end{bmatrix} \begin{bmatrix} A^T & t \\ x_t & x \end{bmatrix} \tag{22}$$

where $A = f_x \;\; f_u H_{uu}{}^1 H_{ux}$, $B = f_u H_{uu}{}^1 f_u{}^T$, $C = H_{xx} \;\; H_{xu} H_{uu}{}^1 H_{ux}$. p_t and p are canceled in Eq.(22).

The derivative of the nonlinear function F with respect to time is given by

$$\frac{dF}{dt} = \;(T;\,t)_t \qquad '_{xx}\;x\,(T;\,t)_t \qquad '_{xp}\;p\,(t+T\,)_t + [\;(T;\,t) \qquad '_{xx}\;x\,(T;\,t) \qquad '_{xp}\;p\;\;(t+T\,)]\,\frac{dT}{dt} \tag{23}$$

The relationship between the costate and other variables is expressed as:

$$_t \qquad = S(\;;\,t)(x_t \qquad x\,) + c(\;;\,t) \tag{24}$$

where

$$\begin{aligned} S &= \;\; A^T S \quad SA + SBS \quad\; C \\ c &= \;\; (A^T \quad SB)c \end{aligned} \tag{25}$$

The following conditions must hold:

$$\begin{aligned} &S(T;\,t) = '_{xx}\,j_{=T}\,; \\ &c(T;\,t) = (H^T_x + ' \qquad f + ' \qquad p\,)\,j \qquad (1 + \frac{dT}{dt}) + A\,F: \end{aligned} \tag{26}$$

$$\frac{d\;(t)}{dt} = \quad H^T_x \;+\; c(0;\,t): \tag{27}$$

The basic idea of the backward sweep method is to integrate Eqs.(17) forward and integrate Eqs.(25) backward along the axis at each time t. Then the di erential equation of (t) is integrated for one step along the t axis so as to determine the optimal control e ort from Eq.(19)

IV. Implementation Method

To demonstrate the outcomes and assess the capabilities of proposed algorithm, the computational power of Simulink and Matlab are utilized. For demonstration of the algorithm, the system at hand has been simpli ed to a xed-direction 2D level ight. The wind is de ned as a constant eastward wind, with a heading of 90^o from true North.

Based on these assumptions, for steady-level ight, the coe cient of lift can be rede ned as:

$$C_L = \frac{2mg}{V^2 S} \tag{28}$$

Additionally, = 0, = 0̄, h is a constant and $\dot{h}$ is zero. Eqs.(1-6) are rewritten with the aforementioned changes incorporated.

$$\dot{V} = \frac{P}{V m} \quad \frac{V^2 S C_{D_0}}{2m} \quad \frac{2mg^2 K}{V^2 S} \quad \dot{W}_V \tag{29}$$

$$\dot{\ } = \frac{\dot{w}}{V} \tag{30}$$

$$\dot{x} = V \sin(\ ) + W_x \tag{31}$$

$$\dot{y} = V \cos(\ ) + W_y \tag{32}$$

The aircraft parameters used for this simulation are similar to those of an MQ-1 Predator drone, however, the powerplant is assumed to be electric so there is no change in mass over the duration of the ight. The aircraft parameters are as follows:

$m = 2250(lb)$
$b = 48{:}7(f\,t)$
$S = 123{:}3(f\,t^2)$
$C_{D_0} = {:}01$
$e = {:}9$
$P_{max} = 63250(\frac{ft\ lbf}{s})$
$C_{L_{max}} = 2{:}2$

Using weighting matrices and reference trajectory tracking parameters, a simulation is conducted to evaluate the desired performance of the proposed real-time optimization algorithm.

V. Results

Through implementation of the real-time non-linear receding horizon control algorithm, the following simulation results are obtained. For this speci c scenario, we demonstrated a constant heading angle ight (= 90[deg]) with a constant East wind (20[ft=sec]). The preliminary results clearly demonstrate the applicability of the algorithm to the system at hand and the power saving bene ts. Given a cost function that penalizes fuel consumption (i.e. power), in presence of any deviation from a desired reference trajectory, the system attempts to minimize the power used to y the aircraft. If the minimum velocity is reached, the aircraft will adjust its power to keep from losing more speed, and maintain minimum power ight, when applicable.

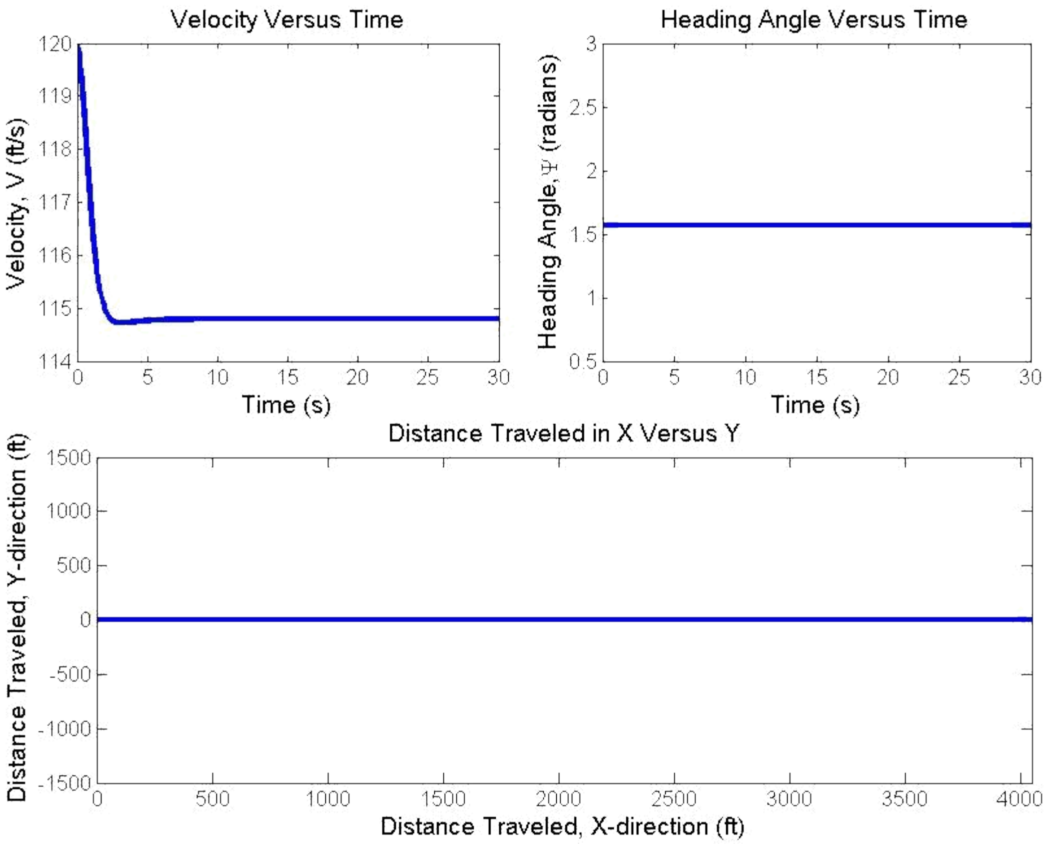

Figure 1. Velocity Versus Time

As can be seen from the Figure-1, for the ight scenario where the wind speed is de ned as 20[ft/sec] (East), aircraft is able to minimize its airspeed and therefore reduce its power consumption, through Eq. (8), while still maintaining its ight course (i.e. xed heading angle). This demonstrates the applicability and bene ts of the concept for power minimization in optimal guidance strategies in the presence of wind.

VI. Conclusion

This paper has presented an approach for a UAV to take advantage of the energy gains available in ying optimal trajectories with respect to current air currents. Aircraft dynamics are modeled by a 3D point mass model, where constant wind is taken into account for level ight conditions. With the utilization of nonlinear receding horizon control methodology and in presence of favourable wind conditions, we demonstrated the reduction in airspeed, which corresponds to minimized value of power, thus fuel savings throughout the ight. In future work, the approach suggested will be extended to include the time varying nature of the wind.

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