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On the Analysis of On-board Sensing and Off-board Sensing through Wireless Communication for UAV Path Planning in Wind Fields

Murilo Augusto Pinheiro*, Mushuang Liu†, Yan Wan‡ and Atilla Dogan§
The University of Texas at Arlington, Arlington, Texas, 76019, USA

We investigate the roles of on-board sensing and off-board sensing through wireless communication for UAV missions. Using UAV path planning in spatiotemporal wind fields as a case study, we construct a modeling framework that includes the communication model that transmits wind map data, vehicle dynamics, and environmental impact. Based on analyzing the minimum-time optimal UAV path planning solution under communication constraints and spatiotemporal wind impact, we obtain quantitative insights into the impact of communication quality and information update configuration on the performance of path planning. We find that on-board sensing and off-board sensing can both improve the the planning performance, however the performance of off-board sensing deteriorates with worsened communication conditions. In addition, the path planing performance can be optimized by appropriately choosing the information update parameters subject to the channel capacity constraints.

I. Nomenclature

L	=	propagation loss
S	=	signal-to-noise Ratio
P_t	=	transmitted power
P_r	=	received power
P_n	=	noise power
G_t	=	transmitter gain
G_r	=	receiver gain
N_p	=	receiver power noise
K_b	=	Boltzmann constant
T	=	temperature
B_W	=	bandwidth
N_n	=	noise figure
C	=	capacity
K	=	number of bits per packet
N	=	number of redundant bits added in each packet
Wx	=	wind speed in the x direction
Wy	=	wind speed in the y direction
x	=	position in the x direction
y	=	position in the y direction
v	=	UAV velocity
ψ_0	=	wind direction at initial time
ω	=	rate of change of the wind direction
ϕ	=	UAV heading angle
$\|W\|$	=	amplitude of wind speed at location (1,1)
X_o	=	x coordinate of initial location

*PhD student, Department of Electrical Engineering.
†PhD student, Department of Electrical Engineering.
‡Associate professor, Department of Electrical Engineering, AIAA Senior Member.
§Associate professor, Department of Mechanical Aerospace Engineering, AIAA Senior Member.

Y_o	=	y coordinate of initial location
X_g	=	x coordinate of destination location
Y_g	=	y coordinate of destination location
λ_x, λ_y	=	lagrange multiplier
H	=	hamiltonian
m	=	filter size
K_l	=	length of control sequence
t_f	=	trajectory duration
τ	=	re-scaled time variable
ϕ^*	=	optimal control sequence

II. Introduction

Unmanned aerial vehicles (UAVs) were originally used for military applications of dangerous, dirty or long-endurance missions. With the recent advancements of UAV technology and consequently cost reduction of its components, the usage of UAVs has rapidly extended to scientific, commercial and civilian domains. UAVs can be considered as moving aerial platforms that carry sensing, communication, computing, and control components [1]. Due to the physical limitations of UAV platforms, such as limited size, payload, and power sources, it becomes impractical for UAVs to conduct all sensing and computing functionalities on board [2]. Off-board sensing and computing at ground stations or other UAVs, and the communication of useful information to on-board UAV systems become a feasible solution. However, many questions remain to understand the roles of on-board and off-board sensing and computation, such as the benefit of off-board information for specific UAV missions, the impact of communication imperfectness, and the optimal configuration of communication services to optimize the overall performance. Insights to such questions can lead to guidelines for UAV traffic management (UTM) in defining the levels of responsibilities, the overall management architectures, and the missions of UAV information service providers.

In this paper, we aim to investigate the roles of on-board sensing and off-board sensing through wireless communication for UAV missions using a quantitative analysis. To do that, we use path planning as an canonical UAV mission for this study. The path planning of UAVs is affected by wind conditions. Currently, most UAV path planning solutions do not consider the knowledge of weather conditions [3], which if exploited, can potentially improve the effectiveness of path planning solutions [4]. Such weather conditions can be obtained using on-board wind sensors [5] or provided by UAV information service providers such as UAV weather stations [6]. Per the best of our knowledge, there are no prior studies that focus on understanding the effects of on-board/off-board sensing and communication performance on UAV path planning. Here we review works in the literature that are related to three aspects of this study, including path planning, wind impact, and UAV wireless communication.

On the aspect of path planning, many studies have been conducted on designing path planning algorithms in different environments [7–10]. Here in this paper, we consider the minimum-time trajectory planning in a spatiotemporal wind field. Related to this direction, Paper [7] considers a Dubins vehicle operating in a time-varying wind field. Based on the Dubins theorem, the author uses an iterative method to calculate the minimum-time trajectory given a corrected heading angle that incorporates the wind field information. Papers [8] and [9] developed their algorithms based on the well-known Zermelo's navigation problem. In [9], the Zermelo's problem solution is integrated with a travelling salesman problem to plan UAV trajectories for structure inspections in windy environments. In paper [8], the Zermelo's problem is studied with constraints to plan trajectories under wind conditions and to avoid flying into restricted areas.

Wind impact can be modeled as stochastic spatiotemporal spread processes [11, 12]. Wind information can be measured on-board using an anemometer or locally estimated [13, 14]. Alternatively, weather service providers can potentially provide wind forecasts that cover larger areas through wireless communication [4]. In the latter case, the range, update, and fidelity of wind information are dependent on communication channel characteristics.

Communication has a fundamental role in enabling weather station to be used as off-board sensor. The communication system performance is related to the spectrum being allocated. In addition, differently from ground communication, the air-to-ground (A2G) channel characteristics are influenced by the altitude, type of UAV, elevation angle and propagation environment conditions [15, 16]. UAV communication has recently drawn significant attention from the community. The studies include the enhancement of communication coverage and capacity, flying UAVs for emergency communication, UAV-to-UAV communication, among others [2, 15, 17–21]. Recent advances include wireless channel modelling and performance analysis, resource management and energy-efficiency, trajectory optimization to enhance optimization, and among others (see e.g., [17, 22]).

The contributions of this paper lie in the following. First, we construct a complete modeling framework that includes the communication channel, vehicle dynamics, and environmental impact, to understand the roles of on-board computing and off-board computing through wireless communication. Second, we develop a minimum-time optimal UAV path planning solution under communication constraints and spatiotemporal wind impact. Third, we use this optimal path planning as a case study to understand the trade-off between wind information availability, i.e. range and update rate, and communication quality in terms of bit error rate (BER), packet error rate (PER) and capacity.

The paper is organized as follows. Section III includes the modeling framework for the communication system. Section IV details the aerial vehicle dynamics, the wind dynamics, and the path planning algorithm. Section V includes the analytical results. Finally, Section VI concludes the paper.

III. Wireless Air-to-Ground Communication Model

In this section, we describe the wireless UAV-to-Ground communication model. We first describe the channel performance model calculated from the signal-to-noise ratio (SNR), and then describe the IEEE802.18 communication protocol used for the UAV-to-Ground communication.

A. Channel Performance Model

The wireless channel performance can be characterized in terms of the signal-to-noise ratio (SNR). The SNR in dB is defined as the difference between the received power and noise power [23],

$$S = P_r - P_n = P_t + G_t + G_r - (L + N_p), \tag{1}$$

where P_t is the transmitting power, G_t and G_r are the gains of the transmitting and receiving antenna respectively. L is the path loss caused by the free-space path loss and shadowing effects. N_p is the noise power at the receiver, which it is a function of the Boltzmann constant (K_b), temperature (T), bandwidth, (B_W), and noise figure (N_n),

$$N_p = 10\log_{10}(K_b T B_W) + N_n \tag{2}$$

Another widely-used channel performance indicator is the channel capacity (C), which is defined as the maximum data rate that can be transmitted through the communication system [16, 23]. The capacity is modeled from the well-known Shannon-Hartley theorem as [23]

$$C = B_W \log_2(1 + S), \tag{3}$$

where C is the capacity in bits per second, and B_W is the bandwidth in Hz.

B. Communication Model

The communication model employed in this paper is inspired by the IEEE802.16 standard, selected by NASA as a promising technology for UAS Control and Non-Payload Communications (CNPC) link [24]. The standard [25] defines both physical and medium control access (MAC) layers. For simplicity, this paper only implements the IEEE802.16 physical layer. The proposed system is composed by two communicating nodes, and thus the upper layers in the communication stack can be summarized to a protocol that creates packets of bits and that implements some basic error detection. The communication model adapted from [26] is shown in Figure 1.

To begin with the communication system model description, the input data, in this case the wind map, is converted to a bit stream for transmission. The wind map is represented by two matrices that capture the wind speed in the longitudinal and latitudinal directions and their length varies according to the range and resolution of the available wind information. Each matrix is transformed into a vector by concatenating its rows together and then each value to be transmitted is converted to binary number using a certain number of bits. The bit sequence generated is then grouped into packets of certain size and a cyclic redundancy check (CRC) is added to the packet to allow the receiver to detect whether the information is correctly received or not.

The overall purpose of the communication system is to transmit information, in this case, the wind map data, from the ground to the UAV. The block diagram of the physical layer of the communication system, presented in Figure 1, is composed of four main blocks: transmitter, air-to-ground channel, receiver and communication performance. The air-to-ground channel block represents the wireless transmission of the wind map data from the ground to UAV. The functions of the other three blocks are described as follows.

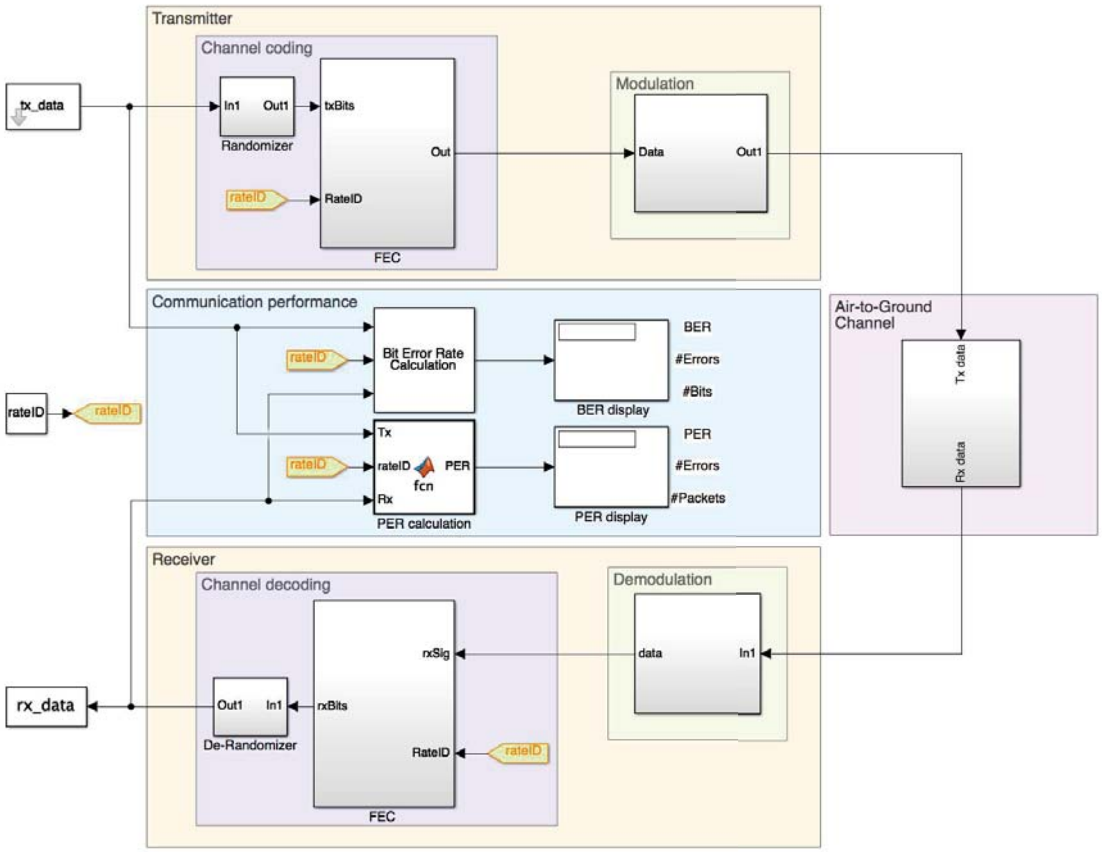


Fig. 1 Block diagram representing the physical layer of the communication model

The transmitter block receives the data to be transmitted in a data stream format (expressed as tx_data), and converts the incoming message into a modulated signal to be transmitted. The process is composed of two sub-blocks, channel coding and modulation. Channel coding is composed of a randomizer, which scrambles the data stream to avoid long runs of zeros or ones and hence facilitates the synchronization procedure between the transmitter and receiver, and a forward error correction (FEC), which is responsible for improving the communication performance and robustness against channel impairments by detecting and correcting random errors as well as burst errors. In particular, FEC generates N redundant bits for every packet of K bits. Thus, it allows an effective code rate of $K/(N+K)$. In addition, FEC guarantees that adjacent sub-carriers are mapped with nonadjacent coded bits and neighbor bits are alternately mapped into less or more significant of the constellation, thus avoid long sequences of unreliable bits. The modulation block modulates the information to be transmitted in the carrier frequencies. The modulation is performed using any of the following modulation techniques: BPSK, QPSK, 16-QAM and 64-QAM. The IEEE 802.16 standard supports an adaptive modulation/coding mechanism that allows the transmission rate to vary according to the channel conditions. The model employed in this paper does not implement this adaptive modulation/coding, enabling the user to select the most convenient scheme. BPSK modulation with a coding scheme with rate $1/2$ is selected in the "rateID" block. After the information is modulated, the data symbols are mapped onto 256 sub-carriers using an inverse fast fourrier transform and a cyclic prefix is inserted to result in the OFDM symbols to be transmitted over the wireless channel.

The receiver block receives the noisy subcarriers from the channel and processes it to retrieve the transmitted information. It is composed of two sub-blocks: demodulation and channel decoding. Demodulation sub-block removes the cyclic prefix and applys the fast Fourier transform to map the OFDM symbols back to the modulated data symbols. The channel decoding sub-block, composed of the FEC and de-randomizer, decodes the information and de-scrambles channel decoding input into the messages received by the UAV.

The communication performance block evaluates the performance of the communication system (i.e., bit error rate (BER) and packet error rate (PER)) by comparing the transmitted and received data streams. BER is calculated by dividing the number of bits received in error by the total number of bits transmitted, while PER is analogically obtained using the number of packets instead of the number of bits. In this work, each packet includes 88 bits ($K = 88$). Figure 2 shows the performance of the communication system in terms of the channel SNR. It can be seen from the figure that 1) both BER and PER decrease with the increase of SNR; 2) with the same SNR value, the BER is always smaller than PER.

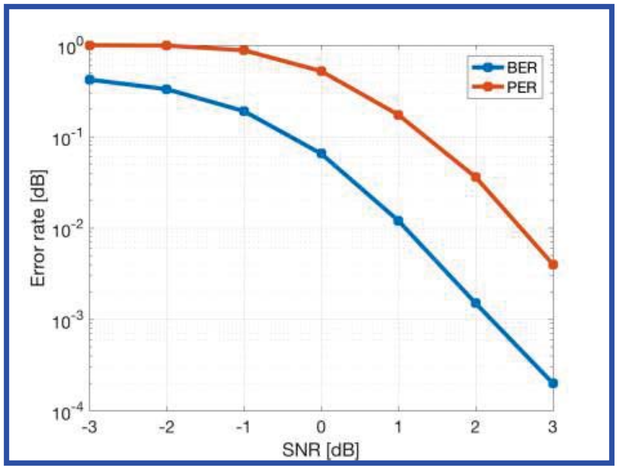


Fig. 2 Communication performance vs channel performance

IV. Path Planning in a Wind Field

We present in this section UAV path planning problem in a spatiotemporal wind field. We describe the UAV dynamics, wind field modeling, received wind map data preparation, and finally the path planning algorithm to minimize the cost (i.e., the trajectory duration).

A. UAV Dynamics

Consider a UAV flying from point A to point B in a two dimensional airspace. The UAV dynamics can be modeled as:

$$\begin{cases} \dot{x}(t) = v(t)\cos\phi(t) + W_x(x, y, t) \\ \dot{y}(t) = v(t)\sin\phi(t) + W_y(x, y, t) \end{cases}, \tag{4}$$

where $x(t)$ and $y(t)$ is the position of UAV in x and y axis respectively. $v(t)$ is the UAV's velocity, and is assumed to be constant $v(t) = V$. $\phi(t)$ is the UAV's heading angle. W_x and W_y is the wind velocity in x and y axis respectively.

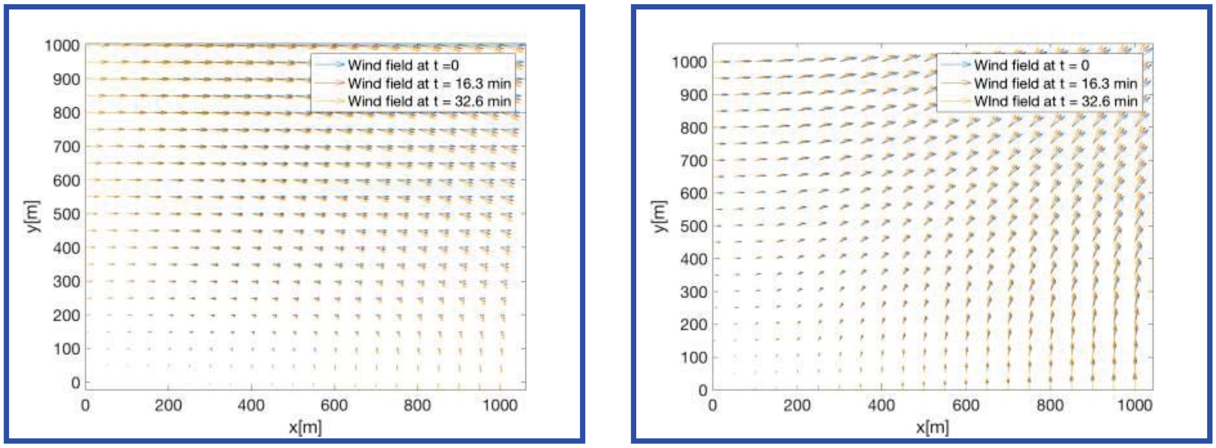
For this particular study, we use a specific spatiotemporal wind dynamics that captures twisted wind spread in all directions, with the purpose of studying spatiotemporal wind impact to the performance of path planning,

$$\begin{cases} W_x(x, y, t) = |W| y \cos(\omega t + \psi_0) \\ W_y(x, y, t) = |W| x \sin(\omega t + \psi_0) \end{cases}, \tag{5}$$

where $|W|$ is the amplitude of wind speed at location $(1, 1)$. To make sure that the UAV's velocity is greater than the wind's velocity, we have $|W|y < V$ and $|W|x < V$. ω is the change rate of the wind direction, and ψ_0 is the wind's initial direction at $t = 0$. Figure 3 illustrates examples of the spatiotemporal wind field modeled when $|W| = 0.01$.

B. Received Wind Map Data Preparation

We consider two approaches to process the received wind map data subject to errors caused by the imperfect communication. In approach 1, the received data with error is directly used. In approach 2, the error information (i.e., the received wrong packet) is discarded. The two approaches correspond to the two performance indicators: BER and PER respectively. For each of these two approaches, a simple filtering procedure is used to process the received wind



(a) $\omega = -0.01$ rad/s and $\psi_0 = 0$ rad   (b) $\omega = 0.01$ rad/s and $\psi_0 = \frac{\pi}{2}$ rad

Fig. 3 Examples of the spatiotemporal wind field.

map data to prepare for path planning. To describe it, we define the wind map as a grid, in which each grid contains the wind speed for a location in the map. Thus, an averaging filter with size m takes the average of the closest $(2m + 1)^2$ grids around each grid in the map to account for the errors and loss of data. The wind speed values near the edges of the map, in which do not have $(2m + 1)^2$ neighbors, are discarded. Figure 4 exemplifies this data preparation procedure.

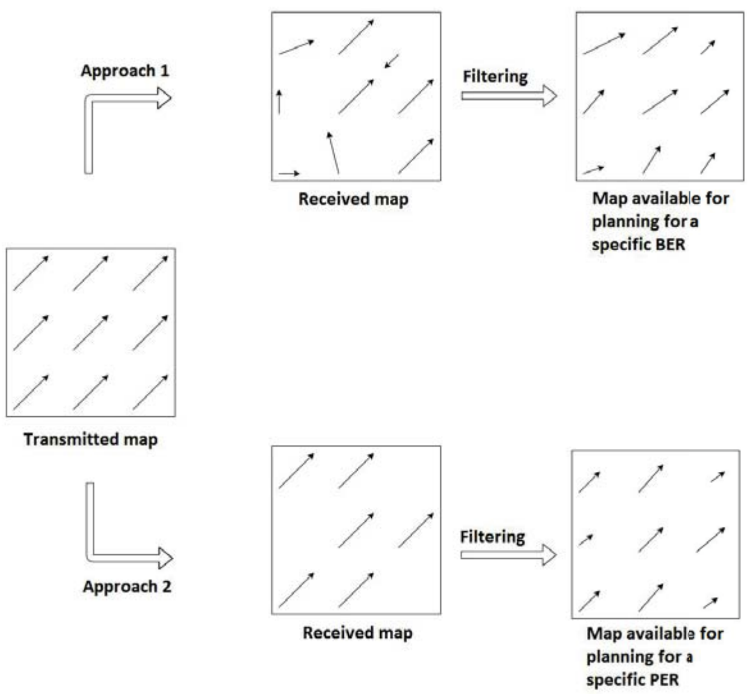


Fig. 4 Differences between BER and PER approaches on the wind map data preparation

Here we introduce the two wind map update parameters that configure the communication service: wind update rate (r_p) and wind map range (l_m). The wind update rate is defined as the number of wind updates per minute. The wind map range is defined as the radius of the wind map centered at the UAV, in meters. Note that as adaptive path planning needs to use the wind data outside the range of the transmitted wind map and the data between discrete wind map data points, extrapolation and interpolation (i.e., the Matlab GriddedInterpolant function) are used here to approximate the unavailable wind information.

C. Optimal Path Planning

Consider the UAV dynamics described in Equation (4). We aim to find the optimal $\phi(t)$ to minimize the trajectory duration for an UAV traveling from the initial position to the destination (see Figure 5). The wind map data is provided through the A2G communication.

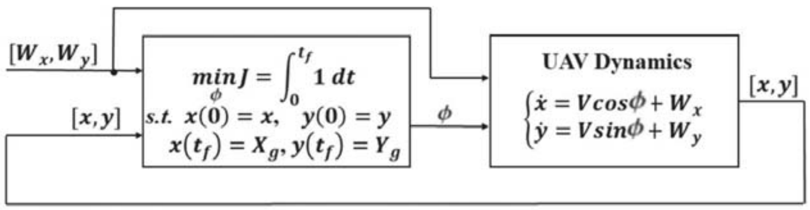


Fig. 5 The block diagram of the UAV control system.

Mathematically, the problem is formulated as [8]:

$$\min_{\phi} J = \int_0^{t_f} 1dt \tag{6}$$

$$\begin{aligned} s.t. \quad & x(0) = X_0, \quad y(0) = Y_0, \\ & x(t_f) = X_g, \quad y(t_f) = Y_g \ , \end{aligned} \tag{7}$$

where (X_0, Y_0) and (X_g, Y_g) are the UAV initial position and the destination position respectively.

We use the Matlab function "fmincon" to solve this optimal control problem. To use the "fmincon" function, the free-final time optimal control problem needs to be transformed into a fixed-final time problem. This transformation is done by re-scaling the time variable t into the re-scaled time variable τ, where $\tau = t/t_f$. With this re-scaling, $\frac{d}{dt}$ should be substituted by $\frac{1}{t_f}\frac{d}{d\tau}$ [27].

This optimal control problem can be solved using the following analytical approach. Given the cost function J and the UAV dynamics shown in Equation (4), the Hamiltonian of the system is [8]:

$$H = \lambda_x(Vcos\phi + W_x) + \lambda_y(Vsin\phi + W_y) + 1 \tag{8}$$

where λ_x and λ_y are Lagrange multipliers. Thus, the costate equations are [8]:

$$\dot{\lambda_x} = -\frac{\partial H}{\partial x} = -\lambda_x\frac{\partial W_x}{\partial x} - \lambda_y\frac{\partial W_y}{\partial x} \tag{9}$$

$$\dot{\lambda_y} = -\frac{\partial H}{\partial y} = -\lambda_x\frac{\partial W_x}{\partial y} - \lambda_y\frac{\partial W_y}{\partial y} \tag{10}$$

$$\frac{\partial H}{\partial \phi} = V(-\lambda_x sin\phi + \lambda_y cos\phi) = 0 \tag{11}$$

Therefore, the Lagrange multiplier can be obtained from Equations (8) and (11) as [8]:

$$\lambda_x = \frac{-cos\theta}{V + W_x cos\phi + W_y sin\phi} \tag{12}$$

$$\lambda_y = \frac{-sin\theta}{V + W_x cos\phi + W_y sin\phi} \tag{13}$$

Equations (12) and (13) can be combined either to (9) or (10) to obtain:

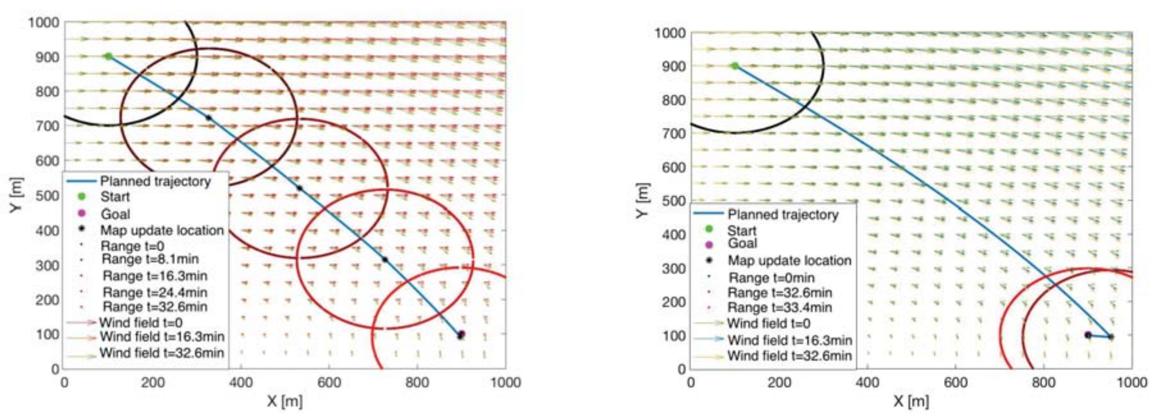
$$\dot{\phi} = sin(\theta^2)\frac{\partial W_y}{\partial x} + sin\phi \cos\phi(\frac{\partial W_x}{\partial x} - \frac{\partial W_y}{\partial y}) - cos(\phi^2)\frac{\partial W_x}{\partial y} \quad (14)$$

The solution of (14) (denoted as ϕ^*), is the optimal control sequence which allows the UAV to traverse from its initial location to the destination in minimal time. Denote the length of the optimal control sequence as K_l, then the control actions in the sequence are spaced by t_f/K_l seconds.

Once the optimal control input sequence ϕ^* is found, it is inputted into the vehicle dynamics to obtain the vehicle trajectory. At each time of the control action update, the algorithm checks if there is an update of the wind map information. If a new map is available, then a new control sequence is recalculated and applied. Note that the control sequence is calculated based on the wind information received from the communication system, which may lead to inaccurate information considering the sensor range, quantization error and imperfect communication channel. If the vehicle does not reach the goal within certain accuracy, the control is also recalculated based on the current vehicle position and wind map, until it reaches the destination or there is a new wind map update (see Algorithm 1). Figure 6 shows two examples of the planned path using the proposed algorithm.

Algorithm 1 Path planning agorithm

1: Set trajectory parameters (i.e., UAV's initial position, goal, and velocity, and sample number K_l), and wind map parameters (map range and update rate).
2: Update wind map.
3: Prepare map by performing extrapolation/interpolation and filtering.
4: Set j=1.
5: Find ϕ^* and t_f based on the received wind map.
6: For each $j \leq K_l$,
    If there is a new map update,
        Go to Step 2.
    Otherwise,
        Implement the j-th control action to the vehicle model.
7: If the destination is reached,
    Stop.
  Otherwise,
    Go to Step 4.



(a) map range = 200m and update rate = 0.1225 updates/min

(b) map range = 200m and update rate = 0.0306 updates/min

Fig. 6 Planned trajectories in the spatiotemporal wind fields

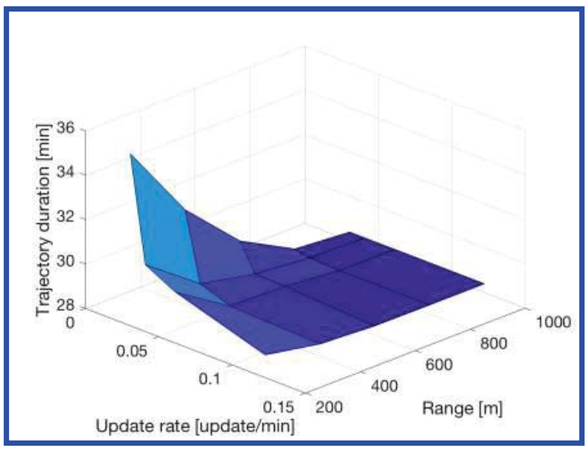
V. Analysis on On-board and Off-board Sensing for UAV Path Planning

We first study the path planning performance in a perfect communication environment, in the sense that the wind map data is not corrupted with noise. When the sensing range is small and update rate is high, this perfect communication case corresponds to on-board sensing as no communication issue exists. The relation between the path planning performance and wind information update parameters (including update rate and update range) are studied. Then we consider the imperfect communication and off-board sensing, and the path planning performance is further studied with different communication environment set-ups (e.g., different SNRs and capacity limits).

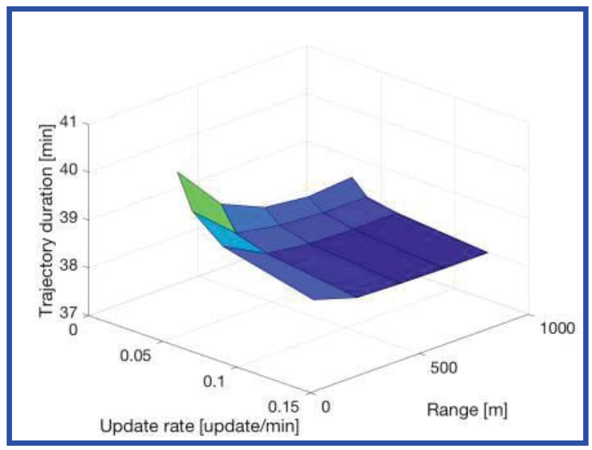
A. Onboard Sensing and Perfect Communication

In the case of perfect communication environment or onboard sensing, two wind scenarios are studied, the time-invariant spatial wind and the spatiotemporal wind. For these two scenarios, the relation between the path planning performance and the information update parameters (i.e. update rate (r_u) and map range (l_m)) is studied respectively. The simulation settings in both scenarios are summarized as follows. The initial location of the UAV is set as $(X_0, Y_0) = (100, 900)$, and the destination is $(X_g, Y_g) = (900, 100)$. The UAV's velocity is set as $v = 25m/s$. The wind magnitude is $|W| = 0.01$, and the wind direction change rate is $\omega = 0$ in the spatial wind scenario, and $\omega = 0.01$ or -0.01 in the spatiotemporal wind scenario. The initial wind direction is set as $\psi_0 = 0°, 90°, 180°$ and $270°$ respectively.

Figures 7a and 7b show the averaged relations between the path planning performance and the update parameters for all spatial wind scenarios with different ψ_0 and all spatiotemporal wind scenarios with different ψ_0 and ω, respectively. It can be seen from the figures that: 1) in both scenarios, the trajectory duration decreases with the increase of the update rate and the map range; 2) compared to the spatiotemporal wind scenario, the spatial wind scenario leads to less trajectory duration, indicating better path planning performance.



(a) Spatial wind scenario



(b) Spatiotemporal wind scenario

Fig. 7 Trajectory duration at different wind map update configurations with perfect communication

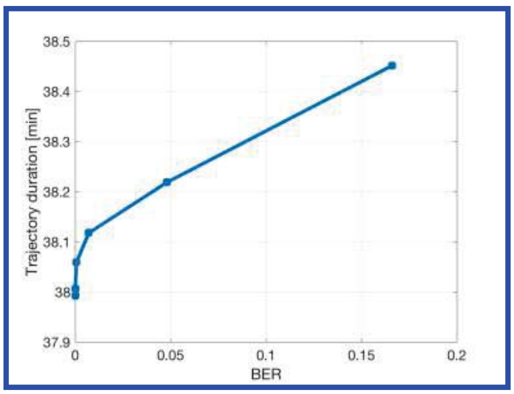
We further study the improvement of path planning performance with the sensed (or transmitted) spatiotemporal wind information. To do that, we compare the trajectory durations for the UAV traveling from the initial position to the destination when 1) the wind information is available, and then 2) the wind information is not available. When the wind information is available, the information update rate is set as $r_u = 0.1225$ updates per minute, with the map range $l_m = 1000m$. The results are shown in Table 1. It can be seen from Table 1 that 1) in all scenarios, the trajectory duration is reduced when the wind information is provided; 2) the performance is improved more (larger difference) when the wind direction is consistent with desired UAV heading direction (e.g., when $\psi_0 = 0°$ and $\psi_0 = 270°$).

B. Off-board Sensing and Imperfect Communication

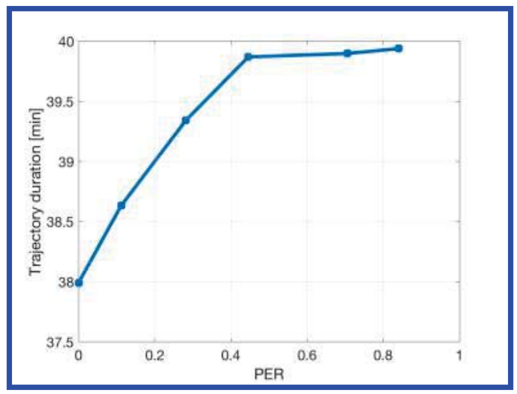
In this section, we study the path planning performance subject to imperfect communication. Figures 8a and 8b show the path planning performance with different BER and PER respectively. When BER and PER are equal to zero, the communication can be considered perfect. It can be seen from the figure that the trajectory duration increases with the increase of both BER and PER.

Table 1 Comparison of the path planning performances

Scenario settings	Trajectory duration with wind information	Trajectory duration without wind information	Difference
$\omega = -0.01$ and $\psi_0 = 0°$	31.57 (*min*)	46.12 (*min*)	14.55 (*min*)
$\omega = -0.01$ and $\psi_0 = 90°$	41.87 (*min*)	47.97 (*min*)	6.10 (*min*)
$\omega = -0.01$ and $\psi_0 = 180°$	44.81 (*min*)	45.96 (*min*)	1.15 (*min*)
$\omega = -0.01$ and $\psi_0 = 270°$	33.52 (*min*)	46.91 (*min*)	13.39 (*min*)
$\omega = 0.01$ and $\psi_0 = 0°$	34.16 (*min*)	46.97 (*min*)	12.81 (*min*)
$\omega = 0.01$ and $\psi_0 = 90°$	43.90 (*min*)	46.97 (*min*)	3.07 (*min*)
$\omega = 0.01$ and $\psi_0 = 180°$	41.74 (*min*)	45.52 (*min*)	3.78 (*min*)
$\omega = 0.01$ and $\psi_0 = 270°$	32.08 (*min*)	47.56 (*min*)	15.48 (*min*)
Average	37.96 (*min*)	46.75 (*min*)	8.79 (*min*)



(a) Using approach 1: BER



(b) Using approach 2: PER

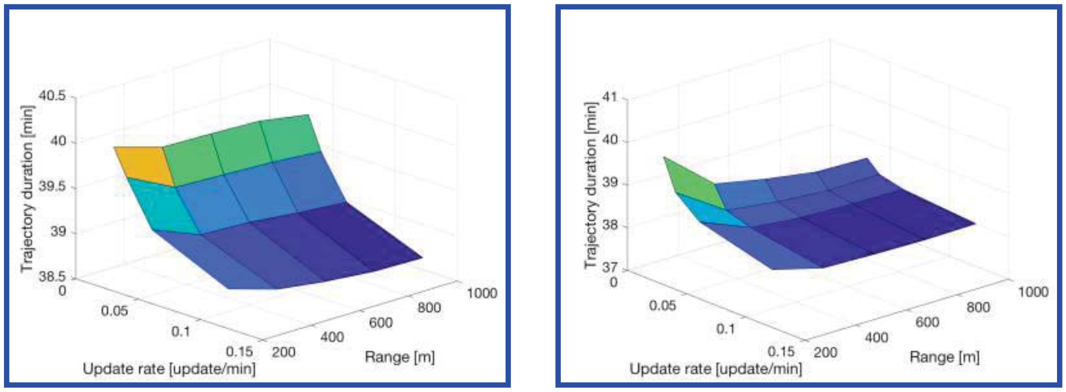
Fig. 8 Trajectory duration with different communication performance

We then study the relation between the path planning performance and the wind update parameters in different communication performance. Figures 9a and 9b show the path planning performance with different map update rates and map ranges, for a specific PER or BER, respectively. It can be seen that the trajectory duration decreases with the increase of the update rate and wind map range in both cases.

We can also optimize the wind map range and update rate (interpreted as configuration of the weather service provision) for the UAVs to navigate in minimum-time to its destination when the communication system has limited capacity. Figure 10a shows the optimal path planning performance (the red dot) with the capacity constraint (maximum 10Mbps). Figure 10b shows the optimal path planning performance (the red dot) with both capacity constraint and the map range constraint (maximum 10Mbps and 0.3 updates/min). From these two figures, one can observe that the optimal setting occurs when the capacity required for transmission is on the boundary of the feasible capacity, which may also hit the wind information update constraints.

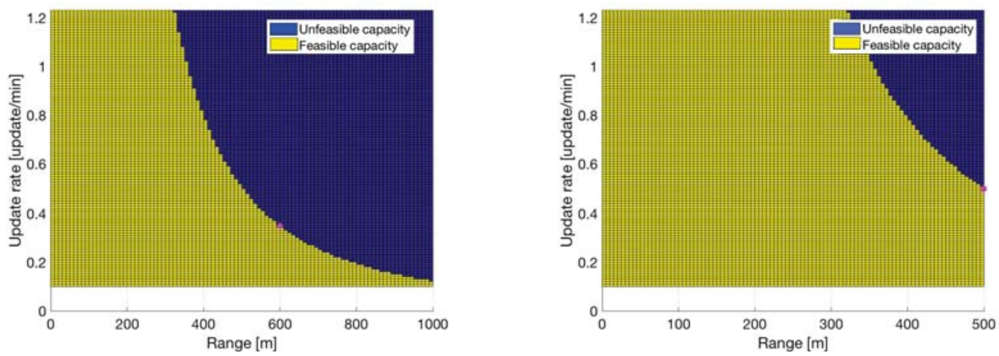
VI. Conclusion

In this paper, we investigated the problem of UAV on-board sensing and off-board sensing through wireless communication, using UAV optimal path planning as a case study. We constructed a modeling framework including the communication channel, vehicle dynamics, and environmental impact. We then developed a minimum-time optimal UAV path planning solution that utilizes on-board or off-board wind map information subject to communication constraints and spatiotemporal wind impact. We find that both on-board sensing and off-board sensing, if properly used, can improve the path planning performance in terms of the trajectory duration. The duration decreases with



(a) packet error rate = 0.112 (b) bit error rate = 4.446e-5

Fig. 9 Trajectory duration at different wind map update configurations with imperfect communication



(a) capacity constraint = 10Mbps (b) capacity constraint = 10 Mbps, and update rate constraint = 0.3 updates/min

Fig. 10 Optimal wind update configurations under various constraints

the increase of the map update rate and map range for the on-board sensing and perfect communication cases. The performance of off-board sensing is significantly affected by the quality of the communication environment. With more limited channel performance measured by SNR and reflected in BER and PER, the trajectory duration of path planning is lengthened. In addition, the path planing performance can be optimized by appropriately configuring the information update parameters (i.e., the update range and update rate) subject to the channel capacity and wind update information configuration constraints. The modeling and analytical framework developed in this paper provides some initial insights on the trade-offs between on-board and off-board sensing. More comprehensive studies will be conducted in the future on the optimal configurations of UAV on-board and off-board sensing and computation, UAV communication, and UAV information service provisions.

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