

Energy-Aware Dynamic Mission Planning Algorithm for UAVs

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Abstract—abstract

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I. INTRODUCTION

Planning a mission for unmanned aerial vehicles (UAVs) operating outdoors is a challenging task. Scenarios such as precision agriculture, search and rescue, and surveillance require advanced levels of autonomy along with strictly limited energy budgets—with the typical instance being a UAV used to inform its grounded counterparts of patterns detected while flying. Currently, UAVs flying outdoors are often semi-autonomous, in the sense that the mission is static and usually defined using a mission planning software [1]. Such a state of practice has prompted us to propose an *energy-aware dynamic mission planning algorithm* for UAVs. The algorithm attempts to combine and generalize some of the past body of knowledge on the mobile robot planning problem, and highlights the increasing *computational demands* and their relation to energy consumption, path, and autonomy.

Planning algorithms for mobile robots broadly are not a new concept, in that they are correlated to such topics as trajectory generation and path planning. Generally, these algorithms select an energy-optimized trajectory [2], by e.g., maximizing the operational time [3], but in practice apply to few robots [4], and focus on optimizing motion control for these robots [5], despite compelling evidence for the systems' energy being influenced by the computations over bare motion [6]. For UAVs specifically, rotorcrafts have equally gained research interest in terms of algorithms for energy-optimized trajectory generation [7], [8]. Furthermore, past mission planning algorithms—which include a broader

concept of a mission being a set of tasks along with a motion plan—also focus on the trajectory [6], [9], and apply to few robots [10], [11]. Yet, computations of such systems are only expected to increase in the near future.

The proposed algorithm alters the energy consumption dynamically by means of mission-specific parameters: the Quality of Service (QoS) of the computations, and the trajectory-explicit equations (TEEs) adjustments. In the remainder of the paper, we strictly adopt the following notation. We refer to the values of mission-specific QoS and TEEs parameters as computations and adjustments, to the constraints sets that delimit such computations and adjustments as QoS and TEEs sets, and to the current trajectory as TEE. Our goal is a mission extension by optimizing both computations and adjustments as the UAV flies and its batteries drain. First, the algorithm optimizes computations requiring the UAV to include robot operating system (ROS) nodes. Then, it optimizes adjustments—a way to alter the trajectory—and guides the UAV using a vector field [12] that converges smoothly to such trajectory. It relies on the assumptions of the mission being *periodic* and *uncertain*. The periodicity is directly observed, by e.g., the UAV flying in repetitive patterns, and the uncertainty accounts for the environmental interference with e.g., a fixed-wing UAV drifting due to windy weather. It addresses the periodicity modeling the energy with Fourier analysis—being the mission periodic, we expect the energy to approximately evolve also periodically—and the uncertainty with a state estimator. It outputs the control input (computations and adjustments) using robust output feedback model predictive control (MPC).

In the spirit of reducing costs, and resources, we showcase the algorithm using the problem of dynamic mission planning for a precision agriculture fixed-wing UAV. Such a scenario is often put into practice [13] with ground mobile robots used for harvesting [14]–[19], and UAVs for preventing damage and ensuring better crop quality [1], [20]. The mission consists of a UAV flying in circles and lines covering a polygon, detecting obstacles using a convolutional neural network (CNN), and informing grounded mobile robots employed for future harvesting—a survey mission optimized for the craft's dynamics. The algorithm plans the mission controlling the processing rate and the radius of the circles, affecting the distance between the lines. Figure 1 shows an initial slice of such a mission. The UAV first heads to a circular TEE with a given radius, which is later reduced, as e.g., windy weather required the adjustment of the control input to avoid battery depletion. Data indicates a potential extension of up to 13 minutes over an hour by merely switching to the lowest computations.

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$$h(k) = \sum_{i=0}^r a_i \cos(ik/\xi) + b_i \sin(ik/\xi), \quad (5)$$

where $\xi \in \mathbb{R}$ is the characteristic time, and $a, b \in \mathbb{R}$ the Fourier series coefficients.

Suppose uncertainty in the form of $\mathbf{w}_k \in \mathbb{R}^m, v_k \in \mathbb{R}$ accounting for the unknown state and output is absent. The non-linear model in Equation (5) can be expressed using an equivalent linear discrete time-invariant state-space model

$$\begin{cases} \mathbf{q}_{k+1} &= A\mathbf{q}_k + B\mathbf{u}_k + \mathbf{w}_k \\ y_k &= C\mathbf{q}_k + v_k \end{cases}, \quad (6)$$

where $y_k \in \mathbb{R}_{\geq 0}$ is the instantaneous energy consumption. The state \mathbf{q} mimics the original Fourier series coefficients

$$\begin{aligned} \mathbf{q}_k &= [\alpha_0 \quad \alpha_1 \quad \beta_1 \quad \cdots \quad \alpha_r \quad \beta_r]^T, \\ A &= \begin{bmatrix} 1 & & & & & \\ & A_1 & & & & \\ & & \ddots & & & \\ & & & A_r & & \end{bmatrix}, \quad A_i = \begin{bmatrix} 0 & \frac{i}{\xi} \\ -\frac{i^2}{\xi^2} & 0 \end{bmatrix}, \\ C &= [1 \quad 1 \quad 0 \quad \cdots \quad 1 \quad 0], \end{aligned} \quad (7)$$

where $\mathbf{q}_k \in \mathbb{R}^m$ given $m := 2r + 1$, $A \in \mathbb{R}^{m \times m}$ is the state transmission matrix, and $C \in \mathbb{R}^m$ is the output matrix. In matrix A , the first value is one, A_i is later on the diagonal, and zero in the remainder.

Suppose at time instant k the mission reached stage i and the control input is $\mathbf{u}_k^a = (\mathbf{c}_k, \mathbf{s}_k)$. The control along with the input matrix

$$\begin{aligned} \mathbf{u}_k &= [g(\mathbf{s}_k) - g(\mathbf{s}_{k-1}) \quad \mathbf{c}_k - \mathbf{c}_{k-1}]^T, \\ B &= \begin{bmatrix} 1 & \omega_{i,1} & \cdots & \omega_{i,\rho} \\ & 0 & & \\ & & \ddots & \\ & & & 0 \end{bmatrix}, \end{aligned} \quad (8)$$

where $\mathbf{s}_k, g(\mathbf{s}_k)$ are defined in Subsection II-C, $\mathbf{u}_k \in \mathbb{R}^n$ is the control given $n := 1 + \rho$, and $B \in \mathbb{R}^{m \times n}$. Moreover, the first item is one, while the others on the first row are gain factors $\omega_i \in \mathbb{R}$, quantifying the contribution of a given adjustment to the instantaneous energy consumption.

Note that the control input $\mathbf{u}_k^a := (\mathbf{c}_k, \mathbf{s}_k)$ —an output of the algorithm—differs from the nominal control in Equation (6) $\mathbf{u}_k(\mathbf{u}_k^a, \mathbf{u}_{k-1}^a)$.

The energy evolution analysis necessitates the following realistic assumption.

Assumption II.1 (Energy evolution periodicity). Given two time instants k_1, k_2 s.t. $k_1 > k_2$ and a constant value $n \in \mathbb{Z}_{>0}$, there exist an arbitrary constant displacement $e \in \mathbb{R}_{\geq 0}$

$$|y_k - y_{k+n}| = e \quad \forall k \in [k_1, k_2]. \quad (9)$$

Physically, the time evolution of the instantaneous energy consumption is assumed periodic, in the sense that it presents repetitive patterns. We show in Section IV the assumption being eased in practice to a set $\mathbb{E} \subset \mathbb{R}$, or omitted under specific conditions.

Equation (8) accounts for the energy due to the computations. The energy due to the adjustments is merely a linear combination of the gain factor ω and the adjustment.

Nevertheless, the change updates the path which will hence affect the reading from the sensors and adjust the state. For instance, a decrement in the adjustment radius of a circle when the TEE is a circle, adds a negative contribution, thus simulates the lowering of instantaneous energy consumption.

C. Energy evolution due to computations

The energy cost of the computations (set of tasks being executed on an embedded board on the UAV) is assessed using `powprofiler`, an open-source modeling tool presented in our previous work [21], that measures software configurations empirically and builds a computational energy consumption model. Specifically, the tool builds a linear interpolation, one per each task. It requires the user to implement the mission as a ROS system with one or more ROS nodes changing the computational load by node-specific ROS parameters.

The mission \mathcal{M} contains a set of ordered lists with tasks (recall Definition II.1). These tasks are simulated by ROS nodes $\Psi(\mathbf{s}_i) := (\psi_1(s_{i,1}), \dots, \psi_\sigma(s_{i,\sigma}))$, in fact they input the desired and output the actual computations

$$\mathbf{s}_i := \{s_{i,1}, \dots, s_{i,\sigma} \mid \psi_j(s_{i,j}) \in \mathbb{S}_i \forall j \in [\sigma]^+\}, \quad (10)$$

where $s_{i,j} : \mathbb{Z}_{\geq 0} \rightarrow \mathbb{Z}_{\geq 0}$ returns the j -th desired computation at stage i , $\mathbf{s}_i \in \mathbb{S}_i \subseteq \mathbb{Z}_{\geq 0}^\sigma$ the union of all QoS sets given $\mathbb{S}_i := \bigcup_{j \in [\sigma]^+} \mathbb{S}_{i,j}$.

Let us further define $g : \mathbb{Z}_{\geq 0} \times \mathbb{Z}_{\geq 0} \rightarrow \mathbb{R}_{\geq 0}$ as the actual instantaneous computational energy consumption value obtained interrogating `powprofiler`

$$y_k^s := g(\Psi(\mathbf{s}_i)) = g(\mathbf{s}_k). \quad (11)$$

Moreover, $g(\{\emptyset\}) = 0$.

III. ALGORITHM

Given an initial stage \mathcal{M}_0 (TEE φ_0 , tasks Ψ , computations $\mathbf{s}_0 \in \mathbb{S}_0$, and adaptations $\mathbf{c}_0 \in \mathbb{C}_0$), the main purpose of the algorithm is to output a set of control input sequence $\mathbf{u}^a := \{\mathbf{u}_0^a, \mathbf{u}_1^a, \dots\}$ in a valid mission.

Definition III.1 (Valid mission). A mission is valid if for every stage \mathcal{M}_{i-1} , $i \in [l]^+$ there exist a control input \mathbf{u}_k^a that produce the next stage \mathcal{M}_i

$$\begin{aligned} \mathbf{u}_k^a &= \{(\mathbf{c}_k, \mathbf{s}_k) \mid (\varphi_i(\mathbf{p}_{k-1}, \mathbf{c}_{i-1}), \Psi(\mathbf{s}_{i-1})) \in \mathcal{M}_{i-1} \\ &\implies (\varphi_i(\mathbf{p}_k, \mathbf{c}_i), \Psi(\mathbf{s}_i)) \in \mathcal{M}_i\}. \end{aligned} \quad (12)$$

Let us proof that if the mission is valid, the instantaneous energy consumption can be modeled as linear combination of the state from the Equation (6).

Theorem III.1 (Periodic energy model). Consider the mission from Definition II.1, the valid mission from III.1. Assume Assumption II.1 holds, the model of Equation (6) behaves ideally ($\mathbf{w} = \mathbf{0}, v = 0$), the initial energy coefficients state \mathbf{q}_0 is y_0^a/m for the first coefficient where $y_0^a \in \mathbb{R}_{>0}$ is an initial measurement¹, $(1/2)y_0^a/m$ for all the others,

¹ y_0^a can be the initial measurement or the measurement from a previous instance of the algorithm

and the mission is valid. Then, the instantaneous energy consumption y_k is a linear combination of the state \mathbf{q}_k .

Proof. The proof is based on mathematical induction. Base case: we proof that $y_0 = y_0^a$. Recall the definition of the state in Equation (7). The output is $y_0 = \alpha_{0,0} + \alpha_{0,1} + \dots + \alpha_{0,r} = y_0^a/m + (1/2)y_0^a/m + \dots + (1/2)y_0^a/m = y_0^a$.

Induction step: by inspection of Equation (6), the output at instant k can be expressed $y_k = (\alpha_{0,0} + B\mathbf{u}_0 + \dots + B\mathbf{u}_{k-1}) + p_1(k)\alpha_{0,1} + \dots + p_r(k)\alpha_{0,r}$, where $\forall t \in \mathbb{Z}_{\geq 2}$

$$p_r(t) := \begin{cases} \prod_{i=1}^{t/2} r^3/\xi^3 & \text{for even } t \\ (r/\xi) \prod_{i=1}^{(t-1)/2} r^3/\xi^3 & \text{for odd } t \end{cases} \quad (13)$$

Suppose k is even and the theorem holds up to k . Initial energy coefficients state \mathbf{q}_0 leads to $y_k = (y_0^a/m + B\mathbf{u}_0 + \dots + B\mathbf{u}_{k-1}) + p_1(k)(1/2)y_0^a/m + \dots + p_r(k)(1/2)y_0^a/m = y_k^a$.

We prove now that the instantaneous energy consumption at $k+1$ is still a linear combination of the state. We express the output in function of the previous state $y_{k+1} = (\alpha_{0,0} + B\mathbf{u}_0 + \dots + B\mathbf{u}_k) + (1/\xi)\beta_{k,1} + \dots + (r/\xi)\beta_{k,r}$. Notice that the coefficients α, β have an equivalent evolution (indeed this allows to simulate the periodicity) and $\beta_{k,r} = p_r(k)\beta_{0,r}$. Thus, the output can be expressed $y_{k+1} = (\alpha_{0,0} + B\mathbf{u}_0 + \dots + B\mathbf{u}_k) + (1/\xi)p_1(k)\beta_{0,1} + \dots + (r/\xi)p_r(k)\beta_{0,r}$. The expression is equivalent to $y_{k+1} = (\alpha_{0,0} + B\mathbf{u}_0 + \dots + B\mathbf{u}_k) + p_r(k+1)\beta_{0,r} + \dots + p_r(k+1)\beta_{0,r}$ using the definition of p_r in Equation (13). Again, the state \mathbf{q}_0 leads to $y_{k+1} = (y_0^a/m + B\mathbf{u}_0 + \dots + B\mathbf{u}_k) + p_r(k+1)(1/2)y_0^a/m + \dots + p_r(k+1)(1/2)y_0^a/m = y_{k+1}^a$, alike the previous statement, but at instant $k+1$. The proof for odd k is equivalent. ■

A. Output constraints set

We stated earlier the output y_k —the instantaneous energy consumption—evolves in $\mathbb{R}_{\geq 0}$. This is generally untrue. Physical UAVs are bounded by strict battery limitations.

Let us hence consider the state of charge (SoC) of such battery with a simplistic difference equation [23]

$$\text{SoC}_k = - \left(V - \sqrt{V^2 - 4R_r \tilde{V} y_k V^{-1}} \right) / 2R_r Q_c, \quad (14)$$

where $V \in \mathbb{R}$ is the internal battery and $\tilde{V} \in \mathbb{R}$ the stabilized voltage, $R_r \in \mathbb{R}$ the resistance, and $Q_c \in \mathbb{R}$ the constant nominal capacity. We define the output constraints set

$$\mathbb{Y}_k := \{y_k \mid y_k \in [0, \text{SoC}_k Q_c V] \subseteq \mathbb{R}_{\geq 0}\}, \quad (15)$$

and $\max \mathbb{Y}_k$ is the maximum discharge capacity by the internal battery voltage—the maximum instantaneous energy consumption.

B. Deployment algorithm

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1: procedure STEP( $\mathbf{q}_{k-1}, \mathbf{u}_{k-1}^a, \mathbf{u}_{k-2}^a, P_{k-1}$ )
2:    $\mathbf{u}_{k-1} \leftarrow \mathbf{u}_{k-1} (\max \mathbf{u}_{k-1}^a, \mathbf{u}_{k-2}^a)$ 
3:    $\mathbf{u}_{k-1}^0 \leftarrow \arg \max_{\mathbf{u}} \sum_{i=k-1}^{k+N-2} l(\mathbf{q}_i, \mathbf{u}_i) + V_f(\mathbf{q}_{k+N-1})$ 
4:    $\hat{\mathbf{q}}_k^- \leftarrow A\hat{\mathbf{q}}_{k-1} + B\mathbf{u}_{k-1}^0$ 
5:   if  $C\hat{\mathbf{q}}_k^- \notin \mathbb{Y}_k$  then
6:      $\mathbf{u}_{k-1}^a \leftarrow \mathbf{u}_{k-1}^a / \{\max \mathbf{u}_{k-1}^a\}$ 

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7:   return STEP( $\mathbf{q}_{k-1}, \mathbf{u}_{k-1}^a, \mathbf{u}_{k-2}^a, P_{k-1}$ )
8: else
9:   if  $|y_k^a - C\hat{\mathbf{q}}_k^-| \leq \varepsilon$  then
10:     $\hat{\mathbf{q}}_k \leftarrow \hat{\mathbf{q}}_k^-$ 
11:     $P_k \leftarrow P_k^-$ 
12:   else
13:     $P_k^- \leftarrow AP_{k-1}A^T + Q$ 
14:     $K \leftarrow P_k^- C^T / (CP_k^- C^T + R)$ 
15:     $\hat{\mathbf{q}}_k \leftarrow \hat{\mathbf{q}}_k^- + K(y_k^a - C\hat{\mathbf{q}}_k^-)$ 
16:     $P_k \leftarrow (I + KC)P_k^-$ 
17:   end if
18:    $\mathbf{u}_k^a \leftarrow \mathbf{u}_{k-1}^a$ 
19:   return ( $\hat{\mathbf{q}}_k, P_k, \mathbf{u}_k^a$ )
20: end if
21: end procedure
22: procedure EADMPA( $\mathcal{M}, \mathbf{p}_0, \mathbf{q}_0$ )
23:    $k \leftarrow 0$ 
24:    $\mathbf{u}_{k-1}^a \leftarrow \{\emptyset\}$ 
25:    $\mathbf{p}_k \leftarrow \mathbf{p}_0$ 
26:    $\mathbf{q}_k \leftarrow \mathbf{q}_0$ 
27:   while  $k \leq t_f$  do
28:      $\mathbf{u}_k^a \leftarrow \{\mathbf{u}_k^a \mid (\varphi_i(\mathbf{p}_k, \mathbf{c}_i), \Psi(\mathbf{s}_i)) \in \lambda(\mathbf{p}_k)\}$ 
29:      $(\mathbf{q}_k, P_k, \mathbf{u}_k^a) \leftarrow \text{STEP}(\mathbf{q}_k, \mathbf{u}_k^a, \mathbf{u}_{k-1}^a, P_k)$ 
30:      $\mathbf{p}_k \leftarrow \mathbf{p}_k \dot{\mathbf{p}}_d(\mathbf{p}_k)/v$ 
31:      $\mathbf{u}_{k-1}^a \leftarrow \mathbf{u}_k^a$ 
32:      $k \leftarrow k + 1$ 
33:   end while
34: end procedure

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Per each time step k (the final time t_f is unknown), the algorithm updates the state—the position at line 30 and the energy coefficients at line 29—and the control input. Note that the position can be computed directly from Equation (4). If the velocity is $v \in \mathbb{R}_{\geq 0}$, and the starting point $\mathbf{p}_0, \mathbf{p}_{k+1} = \mathbf{p}_k \dot{\mathbf{p}}_d(\mathbf{p}_k)/v$.

In detail, initial guess for $P_0 \in \mathbb{R}^{j \times j}$ is positive definite and derived empirically, for \mathbf{q}_0 the initial measurement is distributed to the coefficients (see Theorem III.1). Line 2 selects the maximum possible control from the current control input. Line 3 uses robust output feedback model predictive control (MPC) [24] to select the optimal control \mathbf{u}^0 for a given horizon $N \in \mathbb{Z}_{>0}$ from the cost function

$$l(\mathbf{q}_k, \mathbf{u}_k) := (1/2)(\mathbf{q}_k^T Q \mathbf{q}_k + \mathbf{u}_k^T R \mathbf{u}_k), \quad (16)$$

$$V_f(\mathbf{q}_k) := (1/2)(\mathbf{q}_k^T P_f \mathbf{q}_k),$$

where matrices $Q \in \mathbb{R}^{j \times j}, R \in \mathbb{R}^{l \times l}$ are positive definite.

Follows a check if the mission can finish without the eventuality of battery discharge (output constraints satisfaction) at line 5, with the control input being eventually updated and the process reiterated at line 7.

Before the next step, state estimator—the discrete-time Kalman filter [25] at lines 13–16—predicts the state \mathbf{q} if the modeled instantaneous energy consumption diverges from the sensor's value y_k^a more than a given $\varepsilon \in \mathbb{R}_{\geq 0}$, or sensor measurements are unavailable ($y_k^a = 0$).

IV. RESULTS

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V. CONCLUSION AND FUTURE WORK

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