May 18, 2022

Response letter to the editor and the referees

Dear Referees, Dr. Kurniawati:

We greatly appreciate your time and effort in providing us with an invaluable assessment of our work, helping us to significantly improve both the quality and presentation of our energy-aware planning-scheduling for the aerial robotics domain. We have been able to address all your comments and questions in a revised version that we have attached once again for your kind consideration.

The response letter is split into two sections, each for one review. The referees' comments are in black, and our response is highlighted in blue, similarly to the edits in the attached revised version. The quotes from the revised version are incorporated here in a box with a light red background and a thick red left border.

Thank you for your time and consideration.

Kind regards,

Authors of the manuscript 22-0795

First review

**[R1]** The paper addresses the problem of planning-scheduling for aerial robots with energy awareness for coverage path planning, in which a robot follows a path to cover a polygon. The objective is to maximize the configuration of parameters and satisfy constraints. The authors pose the optimization problem as an MPC and solve for the optimal parameters. They also present an energy model and propose a solution that adjusts the flight path and computational tasks online to deal with energy limitations. This approach extends the energy-aware planning-scheduling to UAVs.

Overall, the paper addresses a very interesting problem and the proposed solution is well-structured. Related work is well reviewed in this letter. Below are some detailed comments and questions.

[R1] We would like to thank the first referee for assessing our work with great detail, proposing edits, and posing important questions. These helped us to strengthen our contribution and clarify aspects we did not consider in the first version.

In this work, we choose to leverage planning-scheduling to aerial robotics, as we believe this is a relevant application and advantageous system for our devised approach. We are thus excited to see the referee sharing similar findings while bringing up numerous important points.

Major Comments:

**[R1:1]** 1. By definition, $t_s$ is the estimated time to complete the coverage, and $t_r$ is the remaining time to complete coverage at time instant $t$. Shouldn't we have $t_r = t_s - t$? However, in line 25 of algorithm 2, $t_r = (t_s/\bar{t})(\bar{t}-t)$. Let's assume that $t_s = \underline{t}$. At time instant $t = \underline{t}$, by line 25, $t_r = (\underline{t}/\bar{t})(\bar{t}-\underline{t}) = \underline{t}-\underline{t}^2/\bar{t} > 0$. This does not make sense since the remaining time $t_r$ should equal to $0$. Could you clarify this?

[R1:1] Thank you for underlying this issue. It is indeed an incorrect transcription of the algorithm, which we have corrected in the revised version. For the sake of clarity, we have further merged line 24 with 25.

> 24: $t_r \leftarrow (\mathrm{diag}(\nu_i^\rho)c_i^\rho(t) + \tau_i^\rho)\overbrace{[1 \quad 1 \quad \cdots \quad 1]}^{\rho} - t$

**[R1:2]** 2. Line 24-27 of algorithm 2 only re-plans $c_i^\rho$. What about $c_i^\sigma$? Since the re-planning is conducted after solving the MPC, optimality can not be claimed for the re-planning. It's possible that there are multiple options to adjust the parameters during re-planning: 1. simultaneously adjusting both $c_i^\rho$ and $c_i^\sigma$; 2. only adjust $c_i^\rho$; 3. only adjust $c_i^\sigma$. It might be useful to consider all of these cases and discuss how they affect optimality.

[R1:2] Thank you for the comment as well as for proposing a way to address the issue. It is correct that in Lines 24–27 we re-plan solely $c_i^\rho$, i.e., the parameters related to the path. The remaining parameters $c_i^\sigma$ related to the computations are then re-planned utilizing the model predictive controller (MPC) in Line 16. The reason why we do not use MPC to plan both the parameters is due to the practical feasibility of re-planning in flight, and due to the different effects of the computation and path parameters on the energy consumption. While the computation parameters have an immediate effect, i.e., they affect the instantaneous energy consumption, the path parameters affect the flight time and thus the overall energy consumption. Concretely and by assumption, a change in the computations alters the schedule, hence the power drained by the computing hardware on the aerial robot, whereas a change in the path parameters alters the time when the aerial robot terminates the coverage.

We have thus decided to utilize a hybrid approach. We employ MPC for the schedule (computation parameters $c_i^\sigma$) and a greedy approach for the coverage (path parameters $c_i^\rho$). Similar combination of techniques has been investigated in the past planning-scheduling literature by Ondrúška et al. (reference

[19] in the revised manuscript). Nonetheless, as underlined in your observation, this was not clear from the text. We have updated the algorithm in Line 16.

> 16: $\mathbf{q}(\mathcal{K} \setminus \{t+N\}), c_i^\sigma(\mathcal{K}) \leftarrow$ solve NLP $\arg\max_{\mathbf{q}(k), c_i(k)}$
> $l_f(\mathbf{q}(t+N), t+N) + \sum_{k \in \mathcal{K}} l_d(\mathbf{q}(k), c_i(k), k)$ in Eq. (18)
> on $\mathcal{K} = \{t, t+h, \ldots, t+N\}$

We have altered the introduction and the problem formulation in Section II to address the observation. We have further added an explanatory text in Section IV.B as well as in the conclusion. In the introduction we have stated explicitly that we utilize both the heuristics and optimal control.

> [...] our approach uses optimal control and heuristics where both the paths and schedules variations are trajectories, varying between given bounds [...] Hybrid approaches [18] are also available, where the techniques are mixed.

We have altered the problem formulation, clearly stating that the objective is to find energy-aware trajectory of parameters rather than optimal.

> [...] the *re-planning-scheduling problem* is finding the energy-aware trajectory of parameters $c_i$ in time, optimizing battery SoC.

We have then altered Section IV.B.

> Past literature on planning-scheduling often relies on optimization as well as heuristics-related approaches [13], [14], [19], [23]. We similarly derive an optimal control problem and a greedy approach returning the trajectory of parameters [...] We utilize MPC to derive the trajectory of the computation parameters and the greedy approach with heuristics remaining coverage time for the path parameters.
>
> An optimal control problem (OCP) that selects the highest configuration of $c_i^\rho$ and respects the constraints [...]
>
> Line 16 in Algorithm 2 contains [...] a nonlinear program (NLP) that can be solved with available NLP solvers [47]. Its solution leads to both trajectories of computation parameters and states [...]
>
> Lines 17–23 estimate the time [...] to [...] drain the battery, [...] The path parameters and thus the coverage is then re-planned accordingly on Lines 24–26 using the heuristics with the scaling factors from Eq. (11) [...]

Finally, we have altered the conclusion.

> Further directions include the use of a purely optimization-based technique, e.g., MPC derives both the path and computation parameters trajectories and the study of different energy models.

**[R1:3]** 3. It is not clear how the parameters of the initial path are obtained. Do the authors use random parameters from the constraint set, or use the highest configuration of parameters? Could you explain the reason for not using the energy-aware planning for the initial trajectory?

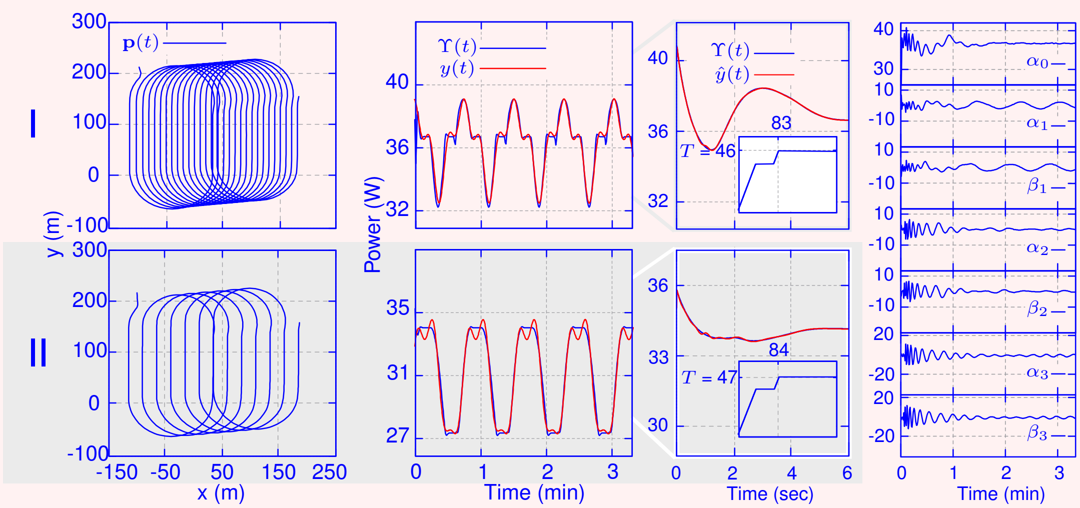
[R1:3] Thank you for observing this omission. We have utilized the highest and the lowest configurations of parameters for the experiments denoted with roman numerals i, I and ii, II respectively, simulating planning-scheduling in the best- and worst-case scenarios. Nonetheless, we do agree it might be advantageous to utilize the algorithm in an ideal simulation first, to estimate the initial parameters.

We have explicitly stated how we obtain the initial configurations in Section V and outlined the possibility of utilizing the methodology to estimate the initial parameters.

> [...] The initial values of path and computation parameters are chosen to represent the highest and lowest configurations in the search space in I–i and II–ii respectively, modeling the behavior of the best- and worst-case scenarios. Different search strategies are possible by, e.g., running an ideal instance of planning-scheduling prior to the flight.

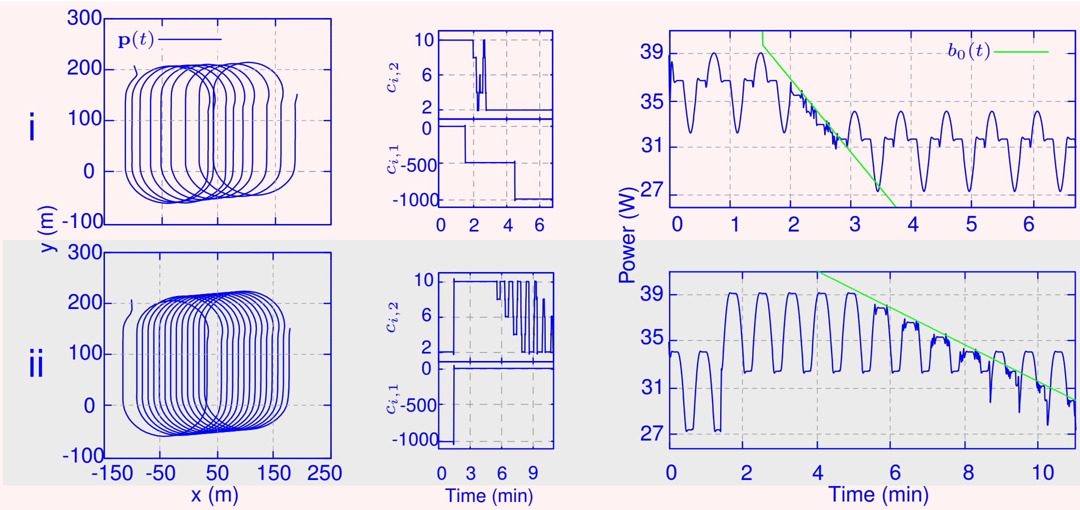
**[R1:4]** 4. The simulation shows some promising results. However, the organization of Fig. 6 makes it difficult to read. For example, what is the top right plot in Fig. 6(b) showing? I understand that there are a number of figures to present and the space is limited, but I would suggest adding legends and axis titles to the plots if possible. You could also consider rewriting the caption of Fig. 6 to make it descriptive enough to be understood. Otherwise, readers have to repeatedly refer to the main text to understand what a specific plot is presenting.

[R1:4] Thank you for the concern regarding the readability of the figure. We have split the figure to address the concern into two Figures, 6 and 7. Subfigures that are related are then on a separate row, each for one case. I,II in Figure 6 are related to CPP at boundary values of path parameters and varying atmospheric conditions, and i,ii Figure 7 are related to planning-scheduling of I,II with varying battery conditions. We have rewritten the captions, adding additional commentary to ease the understanding.




(a) Trajectories without re-planning (b) Energies, detail of first instants, periods $T$ (c) State $(\alpha_0 \cdots \in \mathbf{q})$ evol. for I

Fig. 6: CPP with Zamboni-like motion using two boundary configurations. In a are the trajectories of the coverage–the highest in I and the lowest in II. In b are the energy and the period evolutions for both I and II with different atmospheric conditions. In c are the states that compose the energy model for I.




(a) Re-planned trajectories (b) Parameters $(c_{i,1}, c_{i,2})$ evol. (c) Energies and batteries evol.

Fig. 7: Planning-scheduling of CPP and ground patterns detections, utilizing the lowest configuration I as a starting point in i and the highest II in ii while varying atmospheric (same as Fig. 6) and battery conditions. In a are the re-planned trajectories, in b the parameters, and in c the energy w.r.t. the battery.

**[R1:5]** 5. In line 26, shouldn't the re-planning take place when $t_r > t_b$? In line 27, it is unclear how re-planning is performed. I would suggest having more discussion on this.

[R1:5] Thank you for noting the issue as well as for suggesting more discussion. The former is a typo, and we have fixed the if statement in Algorithm 2.

> 25: **if** $t_r > t_b$ **then**
> 26: $\quad c_i^\rho(t) \leftarrow$ find $c_i^\rho$ with $t_r \in [0, t_b]$, otherwise take $\underline{c}_i^\rho$

To clarify the re-planning of the path parameters, we have added explanatory text in Section IV-B.

> [...] The path parameters and thus the coverage is then re-planned [...] on Lines 24–26 [...] Concretely, these lines implement the greedy approach by decreasing the path parameters of a given value $\delta_i$ or similarly increasing the parameters when $t_r \leq t_b$ within the bounds (this latter analogous case is not shown explicitly in Algorithm 2 but implemented in Sec. V).

We have then detailed the actual value of $\delta_i$ in Section V.

> [...] The set of parameters is unaltered through the flight, i.e, $c_i := \begin{bmatrix} c_{i,1} & c_{i,2} \end{bmatrix}', \forall i$, along $\delta_i$ in the greedy approach.
>
> [...] scaling factors are derived empirically similarly to $\delta_i$ set to two hundred fifty

**[R1:6]** 6. The following paper is related to this letter and the authors could consider referencing it.

- Di Franco, Carmelo, and Giorgio Buttazzo. "Coverage path planning for UAVs photogrammetry with energy and resolution constraints." Journal of Intelligent Robotic Systems 83, no. 3 (2016): 445-462.

[R1:6] Thank you for proposing Di Franco and Buttazzo's past work to our attention. We have considered another past study by the authors "Energy-aware coverage path planning of UAVs" from 2015, and the proposed work appears to be an extension. Both studies do not account for the energy contribution of the computations but interestingly propose the variability of the cover by changing the distance of the survey lines in the boustrophedon motion. Whilst similar to our Zamboni-like motion, the cover variability is not achieved in flight nor applies to constrained aerial robots such as fixed wings–which we consider due to a narrower computation-motion energy difference–but rather rotary wings (they utilize boustrophedon motion).

We have updated the introductory section to include the work comparing both the studies to ours.

> [...] In terms of aerial coverage, past work considers criteria including the completeness of the coverage and resolution [25], and deals with aspects such as the quality of the cover [26], but neglects the energy expenditure of computations and favors rotary-wing aerial robots rather than aerial robots broadly. Such a state of practice has prompted us to propose the planning-scheduling approach for autonomous aerial robots [...]

We have also updated Section IV-A to explicitly state that the variability of the cover is already considered for rotary wings utilizing the boustrophedon motion.

> [...] this section details a [...] motion with a wide turning radius. It is similar to another motion in the literature, the Zamboni motion [42], but additionally allows variable CPP [...] Although cover variability is already considered in the literature [25], it is limited to boustrophedon motion for rotary wings. The novel motion is termed Zamboni-like motion [...]

Minor Comments:

**[R1:7]** 1. In Definition II.1, it would be useful to clarify the use of $j$ and $k$ in the formula of $\Gamma_i$. I assume the authors are saying $c_i^\rho = [c_{i,1}, c_{i,2}, \ldots, c_{i,\rho}]$ and $c_i^\sigma = [c_{i,1}, c_{i,2}, \ldots, c_{i,\sigma}]$, but the definition of $\Gamma_i$ is not quite clear.

[R1:7] Thank you for underlying this issue regarding the definition of stage. We are using the indices $j$ and $k$ to indicate that there might be a different constraint per each parameter and the numbers of parameters $\rho$ and $\sigma$ to indicate that there might be a different number of parameters. Nonetheless, we acknowledge the necessity to exemplify these in a better manner.

We have altered the definition for this purpose.

> **Definition** II.1 (Stage)**.** [...] the $i$th *stage* $\Gamma_i$ is
>
> $$\Gamma_i := \{\varphi_i(\mathbf{p}, c_i^\rho), c_i^\sigma \mid \forall j \in [\rho]_{>0},\, c_{i,j} \in \mathcal{C}_{i,j},\\ \forall k \in [\sigma]_{>0},\, c_{i,\rho+k} \in \mathcal{S}_{i,k}\,\},$$
>
> where $c_i^\rho := \{c_{i,1}, c_{i,2}, \ldots, c_{i,\rho}\}$ and $c_i^\sigma := \{c_{i,\rho+1}, c_{i,\rho+2}, \ldots, c_{i,\rho+\sigma}\}$ are $\rho$ *path* and $\sigma$ *computation parameters*, e.g., $c_i^\rho := \{c_{i,1}\}$ is a value that changes the distance of the coverage lines and $c_i^\sigma := \{c_{i,2}\}$ the detection rate with $\rho$ and $\sigma$ being one (see Section V). $\mathcal{C}_{i,j} := [\underline{c}_{i,j}, \overline{c}_{i,j}] \subseteq \mathbb{R}$ is the $j$th path parameter constraint set, $\mathcal{S}_{i,k} := [\underline{c}_{i,\rho+k}, \overline{c}_{i,\rho+k}] \subseteq \mathbb{Z}_{\geq 0}$ the $k$th computation parameter constraint set. Indices $j, k$ serves to differentiate path and computation parameters constraints and indicate that each parameter can have a different constraint set.

**[R1:8]** 2. By definition $[\rho] = \{0, 1, 2, ..., \rho\}$ is a $\rho + 1$ tuple, implying that $c_i^\rho$, as the second variable of the path function, is a $\rho + 1$ vector in Definition II.1. However, in Definition II.2, it is claimed that the second variable of the path function is a $\rho$-vector.

[R1:8] Thank you for noticing this inconsistency in the notation. We have utilized $[\rho]_{>0}$ with the subscript to indicate a $\rho$ tuple. We have updated the explanatory text after the definition of the stage accordingly.

> [...] The notation $[x]$ denotes positive naturals up to $x$, i.e., $\{0, 1, \ldots, x\}$, $[x]_{>0}$ strictly positive naturals, i.e., $\{1, 2, \ldots, x\}$, [...]

**[R1:9]** 3. I noticed a typo under Definition II.1. "...is the $j$th path parameter $c_{i,j}$ constraint set", should $c_{i,j}$ be removed?

[R1:9] Thank you for noticing the typo. We have removed $c_{i,j}$ from Definition II.1.

**[R1:10]** 4. In Definition II.1, the use of $\mathbf{p}(t)$ is confusing. I assume $\mathbf{p}$ is an arbitrary point on the path, but $\mathbf{p}(t)$ usually refers to a trajectory.

[R1:10] Thank you for underlying the issue. We have not realized this possible source of additional confusion and decided to utilize only $\mathbf{p}$ to designate a point. We have altered the occurrence in the remainder of the work, for consistency. Apart from Definition II.1 that we showed in point 7, the occurrence was in the definition of path functions.

> **Definition II.2** (Path functions). $\varphi_i : \mathbb{R}^2 \times \mathbb{R}^\rho \to \mathbb{R}, \forall i \in \{1, 2, \ldots\}$ are *path functions*, forming the path. They are a function of $\mathbf{p}$ and path parameters $c_i^\rho$ and are continuous and twice differentiable.

In the state-transition function.

> [...] the state-transition function $s : \bigcup_i \Gamma_i \times \mathbb{R}^2 \to \bigcup_i \Gamma_i$ maps a stage and a point to the next stage
>
> $$s(\Gamma_i, \mathbf{p}) := \begin{cases} \Gamma_{i+j} & \text{if } \|\mathbf{p} - \mathbf{p}_{\Gamma_i}\| < \varepsilon_i,\ \exists j \in \mathbb{Z}, \\ \Gamma_i & \text{otherwise.} \end{cases}$$

Finally in Algorithm 1 in lines 2 and 3.

> 2: **if** $\mathbf{p} = \mathbf{p}_{\Gamma_l}$ in Definition II.3 **then return** $\Gamma$
>
> 3: **if** $\mathbf{p} = \mathbf{p}_{\Gamma_i}$ **then**

**[R1:11]** 5. I noticed a typo "computations parameters", I think it should be "computation parameters"

[R1:11] Thank you once again for noticing the typo. We have changed the occurrences of "computations parameters" with "computation parameters", whilst keeping computations when the occurrence indicates multiple computations or when we utilize it to underline, e.g., the energy or schedule of multiple computations.

**[R1:12]** 6. Could you please explain how you obtain matrix $A$ and $C$ in (6) and (7), or put some reference?

[R1:12] Thank you for noticing that a citation and clarification are missing regarding the energy models. The items of matrices $A$ and $C$ are constructed so that the two periodic models, the model in Equation (3) and Equation (4) are equal under some conditions (the value of the initial guess is described by Equation (9) and the model is not perturbed by the control).

We have elaborated further in Section III-A to reflect the observation and added a reference to the corresponding author's previous work.

> [...] Matrices $A$ and $C$ are constructed such that the models in Eqs. (3–4) are equal when $\mathbf{u}$ is a zero vector and an initial guess $\mathbf{q}(t_0) = \mathbf{q}_0$ at initial time instant $t_0$
>
> $$\mathbf{q}_0 = \begin{bmatrix} a_0 & a_1/2 & b_1/2 & \cdots & a_r/2 & b_r/2 \end{bmatrix}', \tag{9}$$
>
> i.e., $h, y$ are both harmonic signals with the same frequencies. Further details see the first author's Ph.D. thesis [31].

**[R1:13]** 7. In line 16 of Algorithm 2, $\mathcal{K} = t, t+h, \ldots, t+N$. It should be $t, t+1, \ldots, t+N$?

8. The definition of $h$ in algorithm 2 is not clear with "the sets $\mathcal{K}, \mathcal{T}$ have possibly different steps $h$". Could you clarify how $h$ is obtained? Is $h$ set to 1, or specified by users?

[R1:13] Thank you for underlying the necessity of further explanation for the steps in $\mathcal{K}, \mathcal{T}$ in both the points 7 and 8. The step for $\mathcal{T}$ is utilized to decide the granularity of re-planning, i.e., how often does the aerial robot finds the configurations of path and computations parameters, whereas the step in $\mathcal{K}$ denotes the integration step for the models in MPC.

Practically, we use a step of one for $\mathcal{T}$, running the re-planning every second, and an integration step of 1/100 fraction of a second, since we express $t_f$ and $N$ both in seconds. We find the parameters so that the re-planning is feasible in real-time and that the numerical simulation does not diverge.

This was not clear in the text, so we have updated Section IV-B according to the observation.

> [...] Here, the sets $\mathcal{K}, \mathcal{T}$ have possibly different steps $h$ (not to be confused with the altitude): the set $\mathcal{K}$ is used for the numerical simulation, whereas $\mathcal{T}$ is for re-planning, meaning that $h$ tunes the precision and the frequency of re-planning in $\mathcal{K}$, $\mathcal{T}$ respectively.

We have then updated Section V.

> [...] $h$ is set to one-hundredth of a second and to one second in $\mathcal{K}, \mathcal{T}$ respectively to allow sufficient precision and re-planning online.

**[R1:14]** 9. By Definition III.2, $g(\cdot)$ has two variables, but equation (12) only has one variable. I assume a time variable is missing

[R1:14] Thank you for noticing the issue. We use the predictive layer function $g(\cdot)$ to return the energy of any possible configuration of computation parameters, independently of the time, given a measuring device (i.e., the computing hardware can measure the energy of different components such as overall, CPU, GPU, memory, etc.).

To construct the predictive layer, we utilize a discrete set of measuring layers $\mathbf{g}(\cdot)$, each containing the time in the form of an interval that specifies for how long a given configuration on a measuring device has to be profiled.

The two variables of $g$ are then the configuration and the specific measuring device, indicated by a positive integer value. We have not realized there might arise confusion between $\mathbf{g}$ and $g$ and thus decided to use $\gamma$ for the measuring layer instead of $\mathbf{g}$ and add further commentary after the equation.

> [...] notation $\lceil c_i^\sigma \rceil, \lfloor c_i^\sigma \rfloor$ indicates two adjacent measurement layers, and $\mathcal{T}_1, \mathcal{T}_2$ are the corresponding

> two time intervals. Measuring device in $\gamma$ and $g$ is not explicitly stated in Eq. (13).

**[R1:15]** 10. There is a typo in the axis title of parameters in Fig. 6(a). The title should be $c_{i,1}$ instead of k$c_{i,1}$

[R1:15] Thank you for noticing the typo. We have fixed the axis title.

**[R1:16]** 11. The way that the authors define $\tau_{i,j}$ and $\nu_{i,j}$ in (10a) and (10b) implies path parameter $c_{i,j}$, $j \in \{1, 2, \ldots, \rho\}$ contributes equally to $t_s$ (defined in line 24 in Algorithm 2). It is difficult to determine if this assumption is reasonable, since $\rho = 1$ in the numerical simulations.

[R1:16] Thank you once again for underlying this point. The assumption was not clearly stated in the manusctipt, and we have thus added additional commentary before the equations.

> We assume that the coverage time evolves linearly and that the path parameters contribute to it equally. $c_i^\rho$ can be then transformed into a time measure with scaling factors [...]

Second reviwew

**[R2]** Contributions:

The contributions of this paper are 1) an energy model that predicts the impact of the effect of changes to the path or computation energy on the battery in the future 2) introduction of Zamboni-like motion patterns that can be replanned while on the path itself 3) an optimal control problem and solution to solve the re-planning coverage problem to decide how to change the computations and the path to optimize the energy usage

[R2] We would like to thank the second referee, especially for the summary of our work and the kind commentary on the relevance and difficulty of accounting for both motion and computations energies in planning for aerial robots. Indeed, we believe that planning-scheduling as a sub-topic of motion planning is still very nascent for aerial robots and hope that this work continues to build upon previous successes in planning-scheduling for mobile robots broadly. To that end, we are excited to comment on and alter the manuscript as necessary, as the second referee brings up a lot of great points.

Related work:

- Good and varied connections made to situate this work in the field.

**[R2:1]** - Not made clear how this is different from other relevant works such as work cited "C. Di Franco and G. Buttazzo, "Energy-aware coverage path planning of UAVs," in Int. Conf. on Autonomous Robot Syst. and Competitions. IEEE, 2015, pp. 111–117"; especially when stating "These studies are focused on ground-based robots [9], [19], [23], [24], yet, aerial robots are particularly affected by energy considerations, as it would be generally required to land to recharge the battery"; since this is not the first with aerial robots, what about this research is different from other work on energy aware CPP? Summarize clearly differences in related work in UAV literature.

[R2:1] Thank you for proposing Di Franco and Buttazzo's past study to our attention. We have considered the work in the original manuscript in terms of the coverage algorithm in Section IV-A, utilizing it as a reference for aerial coverage. We have not included it in the introductory material as the work does not account for the energy expenditure of computations, nonetheless, we agree on the necessity to clarify this in the introduction. To this end, we have added explanatory text in the introduction that–aside the proposed work–includes the follow-up work by the same set of authors proposed by the first referee.

> [...] In terms of aerial coverage, past work considers criteria including the completeness of the coverage and resolution [25], and deals with aspects such as the quality of the cover [26], but neglects the energy expenditure of computations and favors rotary-wing aerial robots rather than aerial robots broadly. Such a state of practice has prompted us to propose the planning-scheduling approach for autonomous aerial robots [...]

We have then explicitly stated the work in Section IV-A in terms of the variability of the cover.

> [...] this section details a [...] motion with a wide turning radius. It is similar to another motion in the literature, the Zamboni motion [42], but additionally allows variable CPP [...] Although cover variability is already considered in the literature [25], it is limited to boustrophedon motion for rotary wings. The novel motion is termed Zamboni-like motion [...]

Strengths:

- This paper addresses a very interesting and practical issue when using UAVs: how to change the behavior of the fixed-wing UAV computations and path w.r.t. to how much battery is left to optimize energy usage.

- Clear preliminaries section helps with understanding technical detail.

- Synthesizes techniques and ideas from various different topics/domains into the challenging replanning coverage problem.

- Technical solution of optimal control problem to manage both computing workloads and path plan interesting and relevant contribution.

- Good simulations with modeling different wind speeds/directions.

Weaknesses:

**[R2:2]** - High-level comment: the paper would benefit from restructuring for clarity to better convey the interesting technical ideas. At present, difficult to understand the insights behind the main contributions. For example, "the re-planning-scheduling problem is finding the optimal trajectory of parameters $c_i$ in time." – optimal w.r.t. what objective function? Total energy? Mission duration? Make this clear in the problem definition section.

[R2:2] Thank you for the high-level comment and for proposing to state clearly the objective function. Regarding the objective function, we have integrated the problem definition accordingly, whereas we have altered the text in the manuscript by both implementing the specific comments and rewriting some technical details or adding further explanatory commentary.

> [...] the *re-planning-scheduling problem* is finding the energy-aware trajectory of parameters $c_i$ in time, optimizing battery SoC.

**[R2:3]** Also, "The energy optimization of computations schedules can be achieved by, e.g., varying the quality of service between specific bounds [12] and frequency and voltage of the computing hardware [9], [13], [14]. We focus on the former aspect and schedule the onboard computations altering their quality while simultaneously changing the quality of the coverage" –> What are the actual computation inputs that can be changed? It is unclear throughout the paper what $c_i^\sigma$ is.

[R2:3] Thank you for underlying the need to state clearly what the computations parameters refer to. We have not realized this point was not stated explicitly in the original version earlier than in the experimental setup. Our purpose is to alter the granularity at which different computations run so that the energy consumption required by the computing hardware onboard the aerial robot increases or decreases.

In our experimental setup, these are the detection rate–meaning we vary the frequency at which a convolutional neural network trained to detect specific hazards runs from two to ten frames per second. These two values are determined empirically, by sampling different boundary configurations and their energy consumption via the modeling tool we describe in Section III-B. We have varied other parameters as well, such as the encryption, utilizing a binary value simply indicating whether the encryption is or is not enabled, and the size of the key in a variable key-size encryption algorithm. However, we have not observed a significant energy drain changing these parameters, conversely to the parameter detection rate. Thus we utilized merely the computation parameter 'detection rate' in our current experimental setup.

We have updated the introductory material to state concretely what computational input is being varied.

> [...] The energy optimization of computations schedules can be achieved by, e.g., varying the quality of service between specific bounds [10] and frequency and voltage of the computing hardware [7], [11], [12]. We focus on the former aspect and schedule the onboard computations altering their quality while simultaneously changing the quality of the coverage. Concretely, we alter how often the aerial robot detects ground patterns along with the distance of the lines that form the coverage. [...]

We have further included the concrete meaning of parameters in Section II.

> **Definition** II.1 (Stage). [...] the $i$th *stage* $\Gamma_i$ is
>
> $$\Gamma_i := \{\varphi_i(\mathbf{p}, c_i^\rho), c_i^\sigma \mid \forall j \in [\rho]_{>0},\, c_{i,j} \in \mathcal{C}_{i,j},\\ \forall k \in [\sigma]_{>0},\, c_{i,\rho+k} \in \mathcal{S}_{i,k}\},$$
>
> where $c_i^\rho := \{c_{i,1}, c_{i,2}, \ldots, c_{i,\rho}\}$ and $c_i^\sigma := \{c_{i,\rho+1}, c_{i,\rho+2}, \ldots, c_{i,\rho+\sigma}\}$ are $\rho$ *path* and $\sigma$ *computation parameters*, e.g., $c_i^\rho := \{c_{i,1}\}$ is a value that changes the distance of the coverage lines and $c_i^\sigma := \{c_{i,2}\}$ the detection rate with $\rho$ and $\sigma$ being one (see Section V). [...]

**[R2:4]** In addition, what is the performance metric we want to observe improving using the algorithm 2 in the numerical experiments (comparing i, ii to I, II baselines)?

[R2:4] Thank you for noticing the comparison was missing in the manuscript. We utilize as a performance metric the weighted average configuration of parameters against the battery state of charge at the end of the flight. We have added explanatory text to the simulation results to report the metric for i and ii against I and II respectively.

> Assuming both the parameters are weighted equally, and the initial battery SoC is seventy percent, I would not be able to complete the flight, and II has a performance metric of zero (i.e., the lowest configuration of parameters throughout the flight). Nonetheless, performance metrics of i and ii are 13.05 and 2.24, whereas the average detection and coverage quality is approx. 45 and 35 for i, and 62 and 87 percent for ii.

**[R2:5]** - Paper would benefit from clear indication of what the performance metric we want to see improve.

[R2:5] Thank you for suggesting adding a clear indication of what performance metrics are being utilized. Indeed this information was missing in the original manuscript. We have added explanatory text in Problem Formulation to address the point.

> The problem is split into two sub-problems: to form a plan that visits every point in space, and re-plan and -schedule the plan in-flight in an energy-aware way. The performance metric the re-planning-scheduling improves is the quality of the plan-schedule against battery state of charge (SoC), e.g., weighted average value of parameters divided by remaining SoC.

**[R2:6]** Average results from more numeric experiments (e.g., average flights competed on baseline vs. with new algorithm) would also really benefit the paper. Paper would also be greatly strengthened by actual physical experiments on UAV.

[R2:6] Thank you for this point; we have reduced the number of experimental results due to space constraints. Nonetheless, we agree that additional results would further justify the need for planning-scheduling in the aerial robotics domain. To this end, we have added the average result for eight flights derived utilizing the flight simulation capabilities of the open-source Paparazzi flight controller. These results are derived in two equally sized sets, each similar to flights i and ii in the manuscript. The results are described thoroughly in the corresponding author's Ph.D. thesis (reference [31], Section 6.3.2.

We have altered the numerical simulation section accordingly.

> Additional results are reported [31] utilizing simulation capabilities of the Paparazzi flight controller. Data are split into two sets of four flights each, one similar to i and the other to ii, i.e., initial parameters are at boundary configurations. These results have an average performance metric of 1.81 and 1.24 for flights similar to i and ii respectively.

We have then reorganized the conclusion, underlining the intent to perform physical experiments at future instances.

> To enable physical experiments, we are currently extending the results to a standard flight controller.

**[R2:7]** - "the Zamboni motion [40], but additionally allows variable CPP at the very core of this work." – need to clarify more why Algorithm 1/Zamboni-like motion is different from Zamboni motion. What is the insight that allows the Zamboni motion to be recalculated/replanned at each stage that isn't possible with regular Zamboni motion in reference [40]?

[R2:7] Thank you for underlying this point. We have not realized that it was not clear in the original manuscript. We use the concept of path parameters as inputs to the path functions that compose the coverage path to ultimately alter the coverage quality dynamically, throughout the flight.

We have added explanatory text to Section IV-A to make this point clear.

> [...] It is similar to another motion in the literature, the *Zamboni motion* [41], but additionally allows variable CPP by dynamically altering the distance between the survey lines with the path parameters. Although cover variability is already considered in the literature [41], it is limited to boustrophedon motion for rotary wings. The novel motion is termed *Zamboni-like motion* and is composed of four primitive paths (see Definition II.5): two lines $\varphi_1, \varphi_2$ and two circles $\varphi_3, \varphi_4$. [...]

Specific edits/typos:

**[R2:8]** - "Such use cases arise in, e.g., precision agriculture [4], where harvesting involves ground vehicles [5], [6], information collection prior to an operation as well as damage prevention during the operation involve aerial robots" is unclear/grammatically incorrect. –> "Such use cases arise in precision agriculture [4] where information collection prior to an harvesting operation and damage prevention during the operation involve aerial robots"

[R2:8] Thank you for spotting the issue in the introductory section. We have corrected the sentence.

> [...] Such use cases arise in precision agriculture [4] where information collection prior to an harvesting operation and damage prevention during the operation involve aerial robots [5], [6].

**[R2:9]** - Figure 1 not clear; are we supposed to be able to differentiate between i, ii, and iii paths? Not able to differentiate currently, so unable to understand key takeaway of figure. What is the meaning of the colors (green for i, red for ii/iii)?

[R2:9] Thank you for noticing the issue regarding poor clarity. We have altered the figure and added a legend to clarify the meaning of i, ii, and iii as different stages in planning-scheduling.

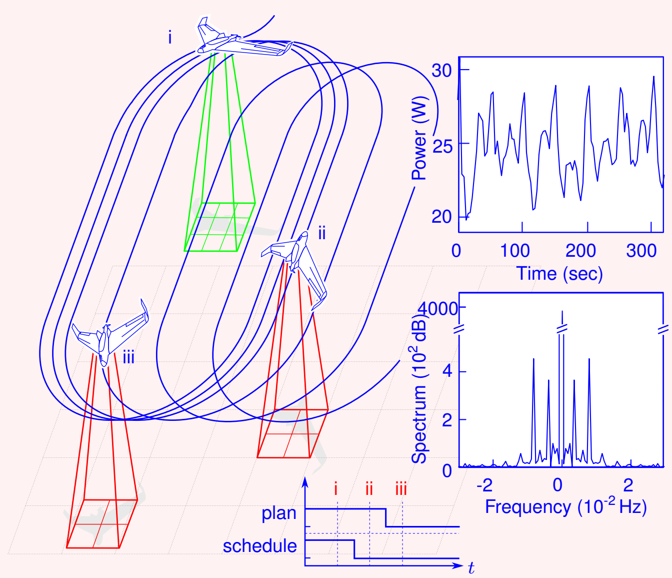



Fig. 1: An initial plan (in i) is re-planned online, changing the detection rate or other computational aspects (in ii) and the number of fly-bys or other motion aspects (in iii). Top-right are the energy data of a physical fixed-wing aerial robot flying a static coverage plan similar to the one illustrated here; below is the spectrum analysis, revealing the periodicity exploited in the energy model.

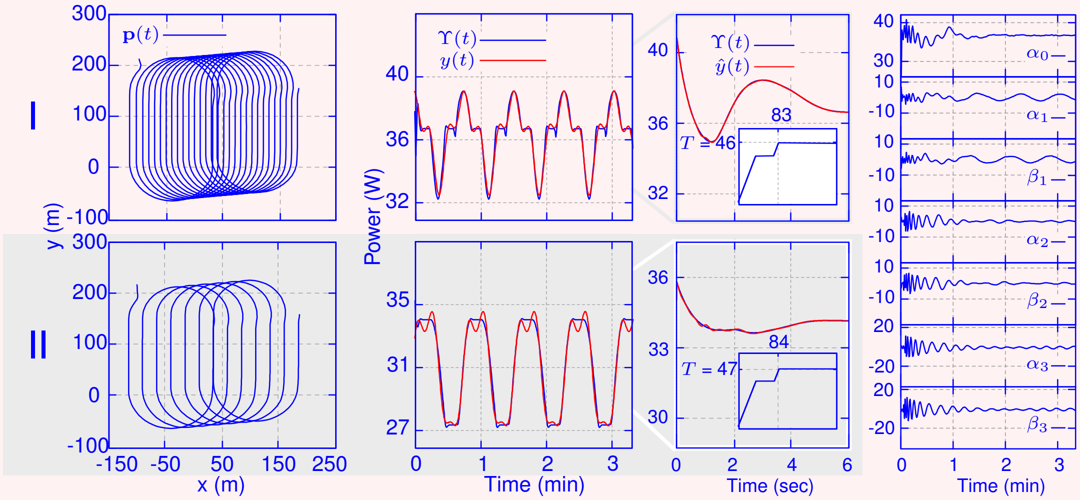
**[R2:10]** - “i.e., when the motion energy contribution far outreaches the computations or vice-versa. The occurrence frequently happens with rotary-wing aerial robots (e.g., quadrotors or quad-copters, hexacopters, etc.) and lighter-than-air aerial robots (e.g., blimps).” –> clarify which example is to which case (motion energy > computing energy for quadrotor, motion energy < computing energy for lighter-than-air)

[R2:10] Thank you for underlying this possible source of confusion. We have fixed the text to clearly state whether the category is in the former or latter occurrence.

> [...] there are other classes where planning-scheduling energy awareness leads to irrelevant savings, i.e., when the motion energy contribution far outreaches the computations or vice-versa. The motion outreaching computation energy frequently happens with rotary-wing aerial robots (e.g., quadrotors or quadcopters, hexacopters, etc.), the opposite occurs with lighter-than-air aerial robots (e.g., blimps). [...]

**[R2:11]** - ordering of figures in Figure 6 is confusing. Consider lumping each case in a separate row (I, i, II, ii).

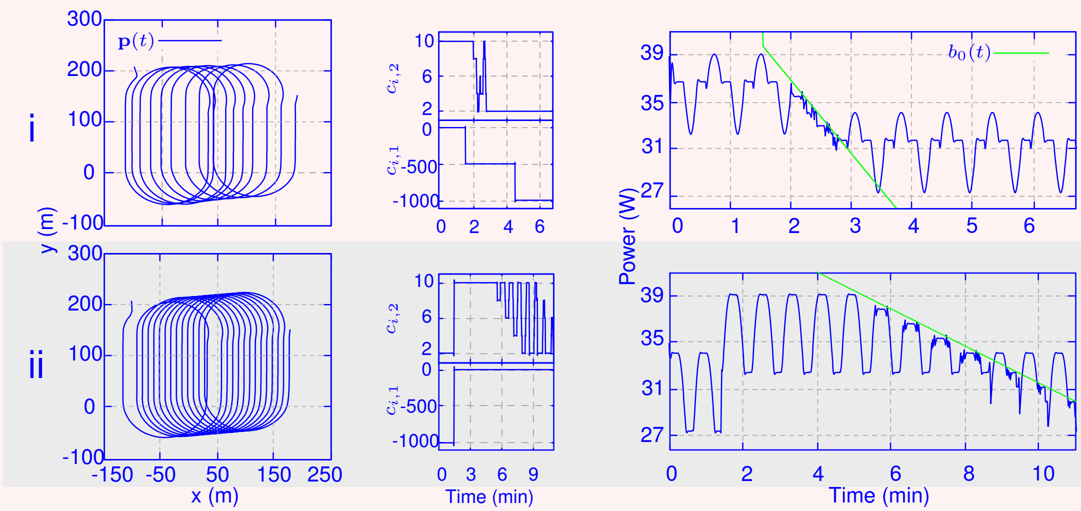
[R2:11] Thank you for underlying the issue. We have attempted to optimize the space but overloaded the figure and significantly reduced its readability. We have reordered Figure 6 to address the issue. We have first split the figure into two Figures, 6 and 7. In both, we utilize one row per case. Figure 6 contains cases I and II related to static coverage at the two boundary configurations under varying wind speeds and directions.




(a) Trajectories without re-planning (b) Energies, detail of first instants, periods $T$ (c) State ($\alpha_0 \cdots \in \mathbf{q}$) evol. for I

Fig. 6: CPP with Zamboni-like motion using two boundary configurations. In a are the trajectories of the coverage–the highest in I and the lowest in II. In b are the energy and the period evolutions for both I and II with different atmospheric conditions. In c are the states that compose the energy model for I.

Figure 7 contains cases i and ii that start from I and II but employ the planning-scheduling in the letter varying battery conditions.




(a) Re-planned trajectories (b) Parameters $(c_{i,1}, c_{i,2})$ evol. (c) Energies and batteries evol.

Fig. 7: Planning-scheduling of CPP and ground patterns detections, utilizing the lowest configuration I as a starting point in i and the highest II in ii while varying atmospheric (same as Fig. 6) and battery conditions. In a are the re-planned trajectories, in b the parameters, and in c the energy w.r.t. the battery.

**[R2:12]** Overall, the paper addresses a very interesting topic and brings together many different techniques to solve a challenging problem. It could be strengthened with more attention to clarity to convey the technical insights and more experiments showing an improvement in a performance metric of interest.

[R2:12] Thank you once again for the commentary as well as for bringing up a lot of important points. We are indeed excited about the potential of planning-scheduling for the aerial robotics domain to address autonomy and other criticalities arising in a number of use cases. We would like to propose a revised version of the manuscript for your kind consideration, where we incorporate the points and additional experimental results.