Automating Bird Diverter Installation through Multi-Aerial Robots and Signal Temporal Logic Specifications

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***Abstract*— This paper tackles the task assignment and trajectory generation problem for bird diverter installation using a fleet of multi-rotors. The proposed motion planner considers payload capacity, recharging constraints, and utilizes Signal Temporal Logic (STL) specifications for encoding mission objectives and temporal requirements. An event-based replanning strategy is introduced to handle unexpected failures and ensure operational continuity. An energy minimization term is also employed to implicitly save multi-rotor flight time during installation. Simulations in MATLAB and Gazebo, as well as field experiments, demonstrate the effectiveness and validity of the approach in a mock-up scenario.**

I. FULL-VERSION

A full version of this work is available at `https://ieeexplore.ieee.org/document/10197369`. To reference, use [1].

II. INTRODUCTION

Power lines are critical infrastructure for supplying energy to millions of people. To enhance network reliability and reduce power outages, installation of bird diverters is crucial to mitigate the risk of bird collisions and improve visibility. However, the current method of using manned helicopters for installation is time-consuming and poses safety risks [2].

Unmanned Aerial Vehicles (UAVs) offer a promising solution for automating and replacing helicopters within the process. UAVs can operate continuously over long distances and can be equipped with lightweight manipulation devices for autonomous operations [3]. However, the limited battery and payload capacity of individual UAVs require the use of multi-UAV teams to expedite the process and cover large-scale scenarios. Planning for a multi-UAV team presents challenges, including scheduling battery recharging, ensuring collision-free trajectories, and considering vehicle dynamics and energy consumption models.

Advanced task and motion planning techniques are necessary to enable bird diverter installation using multi-UAV teams while meeting safety requirements and mission objectives. Signal Temporal Logic (STL), a mathematical framework combining natural language commands with temporal and Boolean operators, can serve this purpose. STL is equipped with a *robustness* metric, quantifying the extent to which system execution meets requirements [4].

Therefore, this paper introduces a novel approach to task and motion planning for installing bird diverters on power lines using a team of multi-rotors. The proposed method leverages STL to generate optimal trajectories that satisfy mission requirements, considering vehicle dynamics, payload capacity limits, and installation time constraints. To ensure continuous operation, an event-based replanning strategy is introduced to handle unforeseen failures. Additionally, an energy minimization term is integrated to save multi-rotor flight time during installation operations. A hierarchical approach is adopt to handle the complexity of the resulting nonlinear optimization problem. First, a Mixed-Integer Linear Programming (MILP) problem is solved, and the resulting solution is fed into the final STL optimizer.

III. PROBLEM DESCRIPTION

The installation of bird diverters involves visiting specific target regions along upper cables between consecutive towers. The UAVs are assumed to be quadrotors with limited velocity, acceleration, and payload capacity. Ground-based refilling stations along the power line provide diverter reloading. The planning process considers vehicle dynamics, capacity constraints, obstacle avoidance, and safety requirements. The environment map, containing obstacles like power towers and cables, is assumed available before the mission.

IV. PROBLEM SOLUTION

Le us define the state sequence $\mathbf{x}$ and the control input sequence $\mathbf{u}$ for the d-th multi-rotor as ${}^{d}\mathbf{x} = ({}^{d}\mathbf{p}^{(1)}, {}^{d}\mathbf{v}^{(1)}, {}^{d}\mathbf{p}^{(2)}, {}^{d}\mathbf{v}^{(2)}, {}^{d}\mathbf{p}^{(3)}, {}^{d}\mathbf{v}^{(3)})^\top$ and ${}^{d}\mathbf{u} = ({}^{d}\mathbf{a}^{(1)}, {}^{d}\mathbf{a}^{(2)}, {}^{d}\mathbf{a}^{(3)})^\top$, where ${}^{d}\mathbf{p}^{(j)}$, ${}^{d}\mathbf{v}^{(j)}$, and ${}^{d}\mathbf{a}^{(j)}$, with $j = \{1, 2, 3\}$, represent the sequences of position, velocity, and acceleration of the vehicle along the j-axis of the world frame, respectively. The k-th elements of ${}^{d}\mathbf{p}^{(j)}$, ${}^{d}\mathbf{v}^{(j)}$, ${}^{d}\mathbf{a}^{(j)}$, and $\mathbf{t}$ are denoted as ${}^{d}p_k^{(j)}$, ${}^{d}v_k^{(j)}$, ${}^{d}a_k^{(j)}$, and t_k, respectively, while the set of drones is denoted as $\mathcal{D}$. Hence, by employing the STL grammar (omitted here for brevity), the outlined bird installation problem is formulated with the STL formula:

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\begin{aligned}
\varphi = & \bigwedge_{d\in\mathcal{D}} \square_{[0,T_N]} \left({}^{d}\varphi_{\mathrm{ws}} \wedge {}^{d}\varphi_{\mathrm{obs}} \wedge {}^{d}\varphi_{\mathrm{dis}}\right) \wedge \\
& \bigwedge_{q=1}^{\mathrm{tr}} \lozenge_{[0,T_N - T_{\mathrm{ins}}]} \bigvee_{d\in\mathcal{D}} \square_{[0,T_{\mathrm{ins}}]} \left({}^{d}c(t_k) > 0\right) {}^{d}\varphi_{\mathrm{tr,q}} \wedge \\
& \bigwedge_{d\in\mathcal{D}} \lozenge_{[0,T_N - T_{\mathrm{rs}}]} \bigvee_{q=1}^{\mathrm{rs}} \square_{[0,T_{\mathrm{rs}}]} \left({}^{d}c(t_k) = 0 \Longrightarrow {}^{d}\mathbf{p}(t_k) \models {}^{d}\varphi_{\mathrm{rs,q}}\right) \wedge \\
& \bigwedge_{d\in\mathcal{D}} \square_{[1,T_N - 1]} \left({}^{d}\mathbf{p}(t_k) \models {}^{d}\varphi_{\mathrm{hm}} \Longrightarrow {}^{d}\mathbf{p}(t_k + 1) \models {}^{d}\varphi_{\mathrm{hm}}\right).
\end{aligned}
\tag{1}
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The STL formula φ comprises both safety and task requirements. The *safety requirements* encompass three aspects: staying within the designated workspace (${}^{d}\varphi_{\mathrm{ws}}$), avoiding collisions with obstacles in the environment (${}^{d}\varphi_{\mathrm{obs}}$), and maintaining a safe distance from other UAVs (${}^{d}\varphi_{\mathrm{dis}}$). On the other hand, the *task requirements* focus on achieving specific tasks at predefined time intervals during the entire mission time T_N. Firstly, they guarantee that all target regions are visited by at least one UAV (${}^{d}\varphi_{\mathrm{tr}}$). Secondly, they ensure that each UAV remains in a target region for the designated installation time T_{ins}, visits a refilling station, and stays there for a refilling time T_{rs} once they exhaust their onboard diverters (${}^{d}\varphi_{\mathrm{rs}}$). Finally, after completing their installation operations, each UAV should fly to the nearest refilling station (${}^{d}\varphi_{\mathrm{hm}}$). The following equations describe each of these specifications:

$$\begin{aligned}
&{}^{d}\varphi_{\mathrm{ws}} = \textstyle\bigwedge_{j=1}^{3} \mathbf{p}^{(j)} \in (\underline{p}_{\mathrm{ws}}^{(j)}, \bar{p}_{\mathrm{ws}}^{(j)}), && \text{(2a)}\\
&{}^{d}\varphi_{\mathrm{obs}} = \textstyle\bigwedge_{j=1}^{3} \bigwedge_{q=1}^{\mathrm{obs}} \mathbf{p}^{(j)} \notin (\underline{p}_{\mathrm{obs,q}}^{(j)}, \bar{p}_{\mathrm{obs,q}}^{(j)}), && \text{(2b)}\\
&{}^{d}\varphi_{\mathrm{dis}} = \textstyle\bigwedge_{\{d,m\}\in\mathcal{D}, d\neq m} \|{}^{d}\mathbf{p} - {}^{m}\mathbf{p}\| \geq \Gamma_{\mathrm{dis}}, && \text{(2c)}\\
&{}^{d}\varphi_{\mathrm{hm}} = \textstyle\bigwedge_{j=1}^{3} \mathbf{p}^{(j)} \in (\underline{p}_{\mathrm{hm}}^{(j)}, \bar{p}_{\mathrm{hm}}^{(j)}), && \text{(2d)}\\
&{}^{d}\varphi_{\mathrm{tr,q}} = \textstyle\bigwedge_{j=1}^{3} {}^{d}\mathbf{p}^{(j)} \in (\underline{p}_{\mathrm{tr,q}}^{(j)}, \bar{p}_{\mathrm{tr,q}}^{(j)}) \wedge \\
&\qquad \wedge \bigcirc_{T_{\mathrm{ins}}} \big({}^{d}c(t_k) = {}^{d}c(t_k - 1) - 1\big), && \text{(2e)}\\
&{}^{d}\varphi_{\mathrm{rs,q}} = \textstyle\bigwedge_{j=1}^{3} \mathbf{p}^{(j)} \in (\underline{p}_{\mathrm{rs,q}}^{(j)}, \bar{p}_{\mathrm{rs,q}}^{(j)}) \wedge \\
&\qquad \wedge \bigcirc_{T_{\mathrm{rs}}} \big({}^{d}c(t_k) = {}^{d}\bar{c}\big), && \text{(2f)}
\end{aligned}$$

where $\underline{p}_{\mathrm{ws}}^{(j)}$, $\bar{p}_{\mathrm{ws}}^{(j)}$, $\underline{p}_{\mathrm{obs,q}}^{(j)}$, $\bar{p}_{\mathrm{obs,q}}^{(j)}$, $\underline{p}_{\mathrm{hm}}^{(j)}$, $\bar{p}_{\mathrm{hm}}^{(j)}$, $\underline{p}_{\mathrm{tr,q}}^{(j)}$, $\bar{p}_{\mathrm{tr,q}}^{(j)}$, $\underline{p}_{\mathrm{rs,q}}^{(j)}$, and $\bar{p}_{\mathrm{rs,q}}^{(j)}$ define the limits of the rectangular regions used for denoting workspace, obstacles, home, target and refilling stations areas; $\Gamma_{\mathrm{dis}} \in \mathbb{R}_{>0}$ represents the threshold value for the mutual distance between UAVs; and ${}^{d}c(t_k)$ refers to the UAVs payload capacity. The label d is used to specify the particular drone to which the STL formula refers, while we refrain from using labels to indicate the vector stack of all drone variables.

Starting from mission specifications encoded as STL formula φ (1), and replacing its robustness $\rho_{\varphi}(\mathbf{x})$ with the smooth approximation $\tilde{\rho}_{\varphi}(\mathbf{x})$, the generation of multi-rotor trajectories can be cast as an optimization problem [5]:

$$\begin{aligned}
&\underset{\substack{\mathbf{p}^{(j)},\, \mathbf{v}^{(j)},\, \mathbf{a}^{(j)} \\ d\in\mathcal{D}}}{\text{maximize}} && \tilde{\rho}_{\varphi}(\mathbf{p}^{(j)}, \mathbf{v}^{(j)})\\
&\text{s.t.} && {}^{d}\underline{v}^{(j)} \leq {}^{d}v_{k}^{(j)} \leq {}^{d}\bar{v}^{(j)},\\
& && {}^{d}\underline{a}^{(j)} \leq {}^{d}a_{k}^{(j)} \leq {}^{d}\bar{a}^{(j)}, \qquad , \qquad \text{(3)}\\
& && \tilde{\rho}_{\varphi}(\mathbf{p}^{(j)}, \mathbf{v}^{(j)}) \geq \varepsilon,\\
& && {}^{d}\mathbf{S}^{(j)}, \forall k = \{0, 1, \ldots, N-1\},
\end{aligned}$$

where ${}^{d}\bar{v}^{(j)}$ and ${}^{d}\bar{a}^{(j)}$ represent the desired maximum values for velocity and acceleration, respectively, of drone d along each j-axis of the world frame. The lower bound on robustness, $\tilde{\rho}_{\varphi}(\mathbf{p}^{(j)}, \mathbf{v}^{(j)}) \geq \varepsilon$, provides a safety margin for satisfying the STL formula φ in the presence of disturbances. Finally, ${}^{d}\mathbf{S}^{(j)}$ refers to the motion primitives employed to describe the motion of drone d along each j-axis [5].

However, the resulting problem is a nonlinear, non-convex max-min optimization problem and solving it within a reasonable time frame is challenging due to the propensity of solvers to converge to local optima [6]. To address this issue, we compute an initial guess using a simplified MILP formulation on a subset of the original specifications φ:

$$\begin{aligned}
&\underset{z_{ij|d},\, y_{j|d}}{\text{minimize}} \quad \sum_{\{i,j\}\in\mathcal{V},\, i\neq j,\, d\in\mathcal{D}} w_{ij|d}\, z_{ij|d} && \text{(4a)}\\
&\text{s.t.} \quad \sum_{i\in\mathcal{V},\, i\neq j,\, d\in\mathcal{D}} z_{ij|d} = 2,\ \forall j \in \mathcal{T}, && \text{(4b)}\\
&\qquad \sum_{i\in\mathcal{V},\, i\neq j} z_{ij|d} = 2y_{j|d},\ \forall j \in \mathcal{T},\ \forall d \in \mathcal{D}, && \text{(4c)}\\
&\qquad \sum_{i\in\mathcal{T}} z_{0i|d} = 1,\ \forall d \in \mathcal{D}, && \text{(4d)}\\
&\qquad \sum_{i\in\mathcal{T},\, j\notin\mathcal{T},\, d\in\mathcal{D}} z_{ij|d} \geq 2h(\mathcal{T})\,. && \text{(4e)}
\end{aligned}$$

The objective function (4a) quantifies the total distance covered by the team. Constraints (4b) and (4c) ensure that each target region is visited exactly once. To achieve this, auxiliary integer variables $y_{j|d} \in \{0, 1\}$ are introduced, which ensure that if a UAV $d \in \mathcal{D}$ reaches target $j \in \mathcal{T}$, the same UAV must also leave the target. Constraint (4d) guarantees that each UAV starts the mission from its depot and does not return to it. Constraints (4e) serve two purposes: preventing tours that exceed the payload capacity of the UAVs and ensuring that all tours connect to a refilling station, which is commonly known as the sub-tour elimination constraint. The lower bound $h(\mathcal{T})$ represents the minimum number of UAVs required to visit all target regions $\mathcal{T}$.

As space is limited, we have excluded the mechanism for mission replanning in the event of UAV failures and the enhancement of the motion planner by minimizing energy consumption. For more information on these aspects, please refer to [1].

V. EXPERIMENTAL RESULTS

The effectiveness and validity of the approach are demonstrated through simulations in MATLAB and Gazebo, as well as field experiments carried out in a mock-up scenario. Videos that can be accessed at `http://mrs.felk.cvut.cz/bird-diverter-ar`.

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