

A framework for power line inspection tasks with multi-robot systems from signal temporal logic specifications

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Abstract—Inspection of power line infrastructures must be periodically conducted by electric companies in order to ensure reliable electric power distribution. Research efforts are focused on automating the power line inspection process by looking for strategies that satisfy different requirements expressed in terms of potential damage and faults detection. This problem comes up with the need of safe planning and control techniques for autonomous robots to perform visual inspection tasks. Such an application becomes even more interesting and of critical importance when considering a multi-robot extension.

In this paper, we propose to compute feasible and constrained trajectories for a fleet of quad-rotors leveraging on Signal Temporal Logic (STL) specifications. The planner allows to formulate rather complex missions avoiding obstacles and forbidden areas along the path. Simulations results achieved in MATLAB show the effectiveness of the proposed approach leading the way to experimental tests on the hardware.

Electric companies invest significantly on the inspection and preemptive maintenance of the power line infrastructure. The most common strategy is to perform aerial inspection of the power line corridor, at regular intervals. The traditional (and the most common) approach to inspection uses a manned helicopter, equipped with multiple sensors, e.g., light and radar sensors, visual, infrared and ultra-violet cameras, mounted on gyroscope stabilized gimbals, and an expert crew, for recording and documenting the relevant data captured from these sensors. This data is later manually examined to detect potential faults and damage on different power line components (e.g., cables, towers, insulators). This process is not only extremely time consuming and dangerous for human operators, but also very expensive (\$1,500 for one hour flight) and prone to human error [1].

In the last two decades, multiple complementary research directions have been explored for automating the task of visual inspection. One key direction has been on developing Unmanned Aerial Vehicles (UAVs) capable of inspecting the power line corridor and the towers [1]. UAVs can execute two different levels of inspections, i.e., macro and micro, depending on the wing type. For example, a fixed-wing UAV cannot hover itself, thus it is used to provide a macro-level

inspection which can be surveying power lines in a large area. On the other hand, a rotary-wing UAV can perform a micro-level inspection such as checking for mechanical failures on transmission components. However, using UAVs to achieve these tasks is particularly challenging due to their limited battery capacity and to the fact that operating close to lines may be impractical for the strong electromagnetic field and the several obstacles (e.g., branches, markers ball) [1].

For all such reasons, having UAVs capable of interpreting high-level, possibly vague, tasks specifications, and nevertheless plan and execute appropriate actions for a particular context in which the system is operating, is more and more important. Symbolic control proposes to fulfill this need by automatically designing feedback controllers that lead to the satisfaction of formal logic specifications. Temporal-logic (TL) based motion planning techniques can be used for this purpose. In particular, Signal Temporal Logic (STL) provides formal high-level languages that can describe planning objectives more complex than well-suited point-to-point navigation algorithms [2]. The task specification is given as a temporal logic formula w.r.t. the discretized abstraction of the robot motion modelled as a finite transition system [3]. Then, a high-level discrete plan is found by off-the-shelf model-checking algorithms [4] given the finite transition system and the task specification. This discrete plan is then implemented through a corresponding low-level hybrid controller.

In this paper, we propose a framework to encode missions for a fleet of quad-rotors as STL specifications. Then, using motion primitives for quad-rotor trajectory generation [5], we construct an optimization problem to generate optimal strategies that satisfy such specifications. The proposed approach generates feasible dynamic trajectories accounting for velocity and accelerations constraints of the vehicles that satisfy missions limitations, too. Simulations results in MATLAB show the effectiveness of the proposed approach.

Let us consider a continuous-time dynamical system \mathcal{H} and its discretized time version $x^+ = f(x, u)$, where $x, x^+ \in X \subset \mathbb{R}^n$ are the current and next state of the system, respectively, $u \in U \subset \mathbb{R}^m$ is the control input and $f: X \times U \rightarrow X$ is differentiable in both arguments. The system's initial state is denoted by x_0 and takes values from some initial set $X_0 \subset \mathbb{R}^n$. Let $T_s = t_{k+1} - t_k$ for all $k \in \mathbb{N}_{\geq 0}$ be the sampling period and $T \in \mathbb{R}_{\geq 0}$ be a trajectory duration, we can write the time interval as $t = (0, T_s, 2T_s, \dots, NT_s)$ with $NT_s = T$. Therefore, given an initial state x_0 and a finite control input sequence $\mathbf{u} = (u_0, u_1, \dots, u_{N-1})$, a trajectory of the system is the unique sequence of states $\mathbf{x} = (x_0, x_1, \dots, x_N)$ with $x_{k+1} = f(x_k, u_k)$.

The trajectory generator is designed to make the closed

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loop system satisfying a specification expressed in STL. STL is a logic that allows the succinct and unambiguous specification of a wide variety of desired system behaviors over time, such as “The quad-rotor reaches the goal within 10 time units while always avoiding obstacles”. Formally, let $M = \{\mu_1, \mu_2, \dots, \mu_L\}$ be a set of real-valued functions of the state $\mu_k: X \rightarrow \mathbb{R}$. For each μ_k define the predicate $p_k := \mu_k(x) \geq 0$. Set $AP := \{p_1, p_2, \dots, p_L\}$. Thus each predicate defines a set over the system state space, namely p_k defines $\{x \in X | \mu_k(x) \geq 0\}$. Let $I \subset \mathbb{R}$ denote a nonsingleton interval, \top the Boolean True, p a predicate, \neg and \wedge the Boolean negation and AND operators, respectively, and \mathcal{U} the Until temporal operator. An STL formula φ is built recursively from the predicates using the grammar $\varphi := \top | p | \neg \varphi | \varphi_1 \wedge \varphi_2 | \varphi_1 \mathcal{U}_I \varphi_2$, where p is a predicate and φ_1 and φ_2 are STL formulas. Informally, $\varphi_1 \mathcal{U}_I \varphi_2$ means that φ_2 must hold at some point in I , and until then, φ_1 must hold without interruption. The disjunction (\vee), implication (\implies), Always (\square) and Eventually (\diamond) operators can be also defined. Formally, the *pointwise semantics* of an STL formula φ defines what it means for a system trajectory \mathbf{x} to satisfy φ [6].

Designing a controller that satisfies a STL formula φ is not always enough. In a dynamic environment, where the system must react to new unforeseen events, it is useful to have a margin of maneuverability. That is, it is useful to control the system such that to maximize a degree of satisfaction of the formula. The latter can be defined and computed using the *robust semantics* of TL [7], [8].

Starting from the definition of a robust STL formula, indicated as $\rho_\varphi(\mathbf{x}, t)$, we can compute control inputs \mathbf{u} by maximizing the robustness over the set of finite state sequences \mathbf{x} . The obtained sequence \mathbf{x}^* is valid if $\rho_\varphi(\mathbf{x}^*, t)$ is positive, where \mathbf{x}^* and \mathbf{u}^* obey to the dynamical system \mathcal{H} . Thus, the goal is to find a provably correct control scheme for a robot system which makes it meeting a control objective φ expressed in temporal logic. So, let $\varepsilon > 0$ be a desired minimum robustness, we solve the following problem

$$\begin{aligned} & \underset{\mathbf{u} \in U^{N-1}}{\text{maximize}} \quad \rho_\varphi(\mathbf{x}) \\ & \text{s.t.} \quad x_{k+1} = f(x_k, u_k), \forall k = \{0, 1, \dots, N-1\}, \\ & \quad x_k \in X, u_k \in U, \forall k = \{0, 1, \dots, N\}, \\ & \quad \rho_\varphi(\mathbf{x}) \geq \varepsilon \end{aligned} \quad (1)$$

The same formalization applies if f , x and u represent the overall dynamics, state and input of a multi-robot system. Because ρ_φ uses the non-differentiable functions max and min [7], [8], solving (1) can be achieved by using Mixed-Integer Programming solvers, non-smooth optimizers or stochastic heuristics [6]. However, as recently shown in [9], it is more efficient and reliable to approximate the non-differentiable objective ρ_φ by a smooth (infinitely differentiable) function $\tilde{\rho}_\varphi$ and to solve the resulting optimization problem using Sequence Quadratic Programming.

To come up with a trajectory that satisfies the vehicle constraints, the motion primitives defined in [5] were considered. Such a method allows to obtain a rapid generation

and feasibility verification of motion primitives for quadrotors. The results of the modified optimization problem is a set of splines [5, eq. (22)] whose parameters can be tuned to achieve a desired motion fixing a combination of position, velocity, and acceleration at the start and end points. Therefore, the objective function can be reformulated replacing $\rho_\varphi(\mathbf{x})$ with its smooth version accounting for the mathematical formulation of the trajectory generator L , i.e., $\tilde{\rho}_\varphi(L(\mathbf{x}))$. To track the obtained references, any of the quadrotor control algorithms within the literature [10] can be used.

We show the effectiveness of the proposed approach through two numerical examples: (i) a multi-drone reach and avoid problem in a constrained environment (eq. (2a), <https://youtu.be/SHTwWkYw1v8>), and (ii) a multi-mission example where several drones have to fly one of two missions in the same environment (see eq. (2b), <https://youtu.be/uqYq5xmCckY>).

$$\begin{aligned} \varphi_{\text{safe}}^{i,j} &= \square_{[0,T]} \varphi_{\text{dist}}^{i,j} = \square_{[0,T]} \left(\| {}^W \mathbf{r}^i - {}^W \mathbf{r}^j \| \geq \delta_{\text{min}} \right), \\ \varphi_{\text{mra}} &= \bigwedge_{k=1}^N \varphi_{\text{ra}}^k \bigwedge \bigwedge_{k=1}^N \left(\bigwedge_{i \neq j} \varphi_{\text{safe}}^{i,j} \right), \end{aligned} \quad (2a)$$

$$\begin{aligned} \varphi_{\text{pli}}^N &= \bigwedge_{k=1}^N \left(\square_{[0,T]} \left(\varphi_{\text{dist}}^k \wedge \varphi_{\text{ws}}^k \right) \right) \bigwedge \diamond_{[0,T]} \left(\left(\bigwedge_{k=1}^{N/2} \varphi_{\text{pole1}}^k \wedge \varphi_{\text{pole4}}^k \right) \right. \\ & \quad \left. \bigwedge \left(\bigwedge_{k=N/2+1}^N \varphi_{\text{pole2}}^k \wedge \varphi_{\text{pole3}}^k \right) \mathcal{U}_{[0,T/2]} \left(\bigwedge_{k=N/2+1}^N \varphi_{\text{pole3}}^k \wedge \varphi_{\text{pole2}}^k \right) \right) \end{aligned} \quad (2b)$$

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