

Large-Scale Robust Sequential Path Planning

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Abstract—Provably safe and scalable multi-vehicle path planning is an important and urgent problem due to the expected increase of automation in civilian airspace in the near future. Hamilton-Jacobi (HJ) reachability is an ideal tool for analyzing such safety-critical systems and has been successfully applied to several small-scale problems. However, a direct application of HJ reachability to large scale systems is often intractable because of its exponentially-scaling computation complexity with respect to system dimension, also known as the ‘curse of dimensionality.’ To overcome this problem, the sequential path planning (SPP) method, which assigns strict priorities to vehicles, was proposed; SPP allows multi-vehicle path planning to be done with a linearly-scaling computation complexity. In this work, we demonstrate the potential of SPP algorithm as a trajectory planning algorithm for large-scale systems. In particular, we simulate large-scale multi-vehicle systems in two different urban environments, a city environment and a multi-city environment, and use SPP algorithm for trajectory planning. SPP algorithm is able to efficiently design collision-free trajectories in both environments despite the presence of disturbances in vehicles’ dynamics. To ensure a safe transition of vehicles to their destinations, it automatically allocates a space-time reservation to vehicles based on the magnitude of disturbance. This leads to a multi-lane division of airspace, where the number of lanes depends on the disturbance and other problem parameters.

I. INTRODUCTION

Recently, there has been an immense surge of interest in the use of unmanned aerial systems (UASs) for civil applications. The applications include package delivery, aerial surveillance, disaster response, among many others [1]–[5]. Unlike previous uses of UASs for military purposes, civil applications will involve unmanned aerial vehicles (UAVs) flying in urban environments, potentially in close proximity of humans, other UAVs, and other important assets. As a result, government agencies such as the Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) of the United States are urgently trying to develop new scalable ways to organize an airspace in which potentially thousands of UAVs can fly together [6], [7].

One essential problem that needs to be addressed for this endeavour to be successful is that of trajectory planning: how a group of vehicles in the same vicinity can reach their destinations while avoiding situations which are considered dangerous, such as collisions. Many previous studies address this problem under different assumptions. In some studies,

specific control strategies for the vehicles are assumed, and approaches such as those involving induced velocity obstacles [8]–[11] and involving virtual potential fields to maintain collision avoidance [12], [13] have been used. Methods have also been proposed for real-time trajectory generation [14], for path planning for vehicles with linear dynamics in the presence of obstacles with known motion [15], and for cooperative path planning via waypoints which do not account for vehicle dynamics [16]. Other related work include those which consider only the collision avoidance problem without path planning. These results include those that assume the system has a linear model [17]–[19], rely on a linearization of the system model [20], [21], assume a simple positional state space [22], and many others [23]–[25].

However, to make sure that a dense group of UAVs can safely fly in the close vicinity of each other, we need the capability to flexibly plan provably safe and dynamically feasible trajectories without making strong assumptions on the vehicles’ dynamics and other vehicles’ motion. Moreover, any trajectory planning scheme that addresses collision avoidance must also guarantee both goal satisfaction and safety of UAVs despite disturbances caused by wind and communication faults [7]. Finally, the proposed scheme should scale well with the number of vehicles.

The problem of trajectory planning and collision avoidance under disturbances in safety-critical systems has been studied using Hamilton-Jacobi (HJ) reachability analysis, which provides guarantees on goal satisfaction and safety of optimal system trajectories [26]–[31]. Reachability-based methods are particularly suitable in the context of UAVs because of the hard guarantees that are provided. In reachability analysis, one computes the reach-avoid set, defined as the set of states from which the system can be driven to a target set while satisfying (possibly time-varying) state constraints at all times. A major practical appeal of this approach stems from the availability of modern numerical tools, which can compute various definitions of reachable sets [32]–[35]. These numerical tools, for example, have been successfully used to solve a variety of differential games, path planning problems, and optimal control problems. Concrete practical applications include aircraft auto-landing [36], automated aerial refueling [37], MPC control of quadrotors [38], and multiplayer reach-avoid games [39]. Despite its power, the approach becomes numerically intractable as the state space dimension increases. In particular, reachable set computations involve solving a HJ partial differential equation (PDE) or variational inequality (VI) on a grid representing a discretization of the state space, resulting in an *exponential* scaling of computational complexity with respect to the dimensionality of the problem. Therefore, as such, dynamic programming-based approaches such as reachability analysis are not suitable for managing the

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next generation airspace, which is a large-scale system with a high-dimensional joint state space because of the high density of vehicles that needs to be accommodated [7].

To overcome this problem, Sequential Path Planning (SPP) method has been proposed [40], in which vehicles are assigned a strict priority ordering. Higher-priority vehicles plan their paths without taking into account the lower-priority vehicles. Lower-priority vehicles treat higher-priority vehicles as moving obstacles. Under this assumption, time-varying formulations of reachability [29], [31] can be used to obtain the optimal and provably safe paths for each vehicle, starting from the highest-priority vehicle. Thus, the curse of dimensionality is overcome for the multi-vehicle path planning problem at the cost of a mild structural assumption, under which the computation complexity scales just *linearly* with the number of vehicles. Intuitively, SPP algorithm allocates a space-time trajectory to each vehicle based on their priorities. The highest priority vehicle gets to choose whatever space-time trajectory is optimal for it. The next vehicle can also choose its optimal trajectory but such that it doesn't intersect with the trajectory of the highest priority vehicle, and so on. Hence two vehicles can either follow same state trajectory but at different times (referred to as *time-separated* trajectories here on) or follow different state trajectories but at the same time (referred to as *state-separated* trajectories here on), but not both. Finally, they can have different state trajectories at different times (referred to as *state-time separated* trajectories here on). So by design, SPP algorithm ensures that the space-time trajectories of the vehicles do not intersect, and hence a safe transition to destination is guaranteed.

Authors in [41] and [42], respectively, extend SPP to the scenarios where disturbances and adversarial intruders are present in the system, resolving some of the practical challenges associated with the basic SPP algorithm in [40]. The focus of these works, however, have mostly been on the theoretical development of SPP algorithm. Our focus in this work is instead on demonstrating the potential of SPP algorithm as a provably safe trajectory planning algorithm for large-scale systems. In particular, our main contributions in this work are:

- we simulate large-scale multi-vehicle systems in two different urban environments under the presence of disturbances in vehicles' dynamics. First, SPP algorithm is used for trajectory planning at a city level and then at a regional level. For city level planning, we consider the San Francisco city in California, US and for regional level planning we consider the entire Bay area in California, US. The main differences emerge from the fact that the city level planning needs to take into account physical obstacles (like buildings, etc.), whereas there are fewer obstacles at a regional level, but the origins and destinations are farther apart. In both cases, we demonstrate that SPP algorithm is able to design provably-safe trajectories despite the disturbances.
- we demonstrate how different types of space-time trajectories emerge automatically out of SPP algorithm between a given pair of origin and destination for different disturbance conditions and other problem parameters.

- we also show the reactivity of the control law obtained from SPP algorithm, i.e., the obtained control law is able to effectively counter the disturbances in real-time without requiring any communication with other vehicles.

Rest of the paper is organized as follows: in Section II, we formally present the SPP problem in the presence of disturbances. In Section III, we present a brief review of time-varying reachability, the basic SPP algorithm [40] in the absence of disturbances, and the Robust Trajectory Tracking (RTT) method [41] to account for disturbances. We also use this algorithm for all our simulations in this paper. All simulation results are in Section ??.

II. SEQUENTIAL PATH PLANNING PROBLEM

Consider N vehicles (also denoted as *SPP vehicles*) which participate in the SPP process $Q_i, i = 1, \dots, N$. We assume their dynamics are given by

$$\begin{aligned} \dot{x}_i &= f_i(x_i, u_i, d_i), t \leq t_i^{\text{STA}} \\ u_i &\in \mathcal{U}_i, d_i \in \mathcal{D}_i, i = 1 \dots, N \end{aligned} \quad (1)$$

where $x_i \in \mathbb{R}^{n_i}$, $u_i \in \mathcal{U}_i$ and $d_i \in \mathcal{D}_i$, respectively, represent the state, control and disturbance experienced by vehicle Q_i . We partition the state x_i into the position component $p_i \in \mathbb{R}^{n_p}$ and the non-position component $h_i \in \mathbb{R}^{n_i - n_p}$: $x_i = (p_i, h_i)$. We will use the sets $\mathcal{U}_i, \mathcal{D}_i$ to respectively denote the set of functions from which the control and disturbance functions $u_i(\cdot), d_i(\cdot)$ are drawn.

Each vehicle Q_i has initial state x_i^0 , and aims to reach its target \mathcal{L}_i by some scheduled time of arrival t_i^{STA} . The target in general represents some set of desirable states, for example the destination of Q_i . On its way to \mathcal{L}_i , Q_i must avoid a set of static obstacles $\mathcal{O}_i^{\text{static}} \subset \mathbb{R}^{n_i}$. The interpretation of $\mathcal{O}_i^{\text{static}}$ could be a tall building or any set of states that are forbidden for each SPP vehicle. In addition to the static obstacles, each vehicle Q_i must also avoid the danger zones with respect to every other vehicle $Q_j, j \neq i$. The danger zones in general can represent any joint configurations between Q_i and Q_j that are considered to be unsafe. We define the danger zone of Q_i with respect to Q_j to be

$$\mathcal{Z}_{ij} = \{(x_i, x_j) : \|p_i - p_j\|_2 \leq R_c\} \quad (2)$$

whose interpretation is that Q_i and Q_j are considered to be in an unsafe configuration when they are within a distance of R_c of each other. In particular, Q_i and Q_j are said to have collided, iff $(x_i, x_j) \in \mathcal{Z}_{ij}$.

Given the set of SPP vehicles, their targets \mathcal{L}_i , the static obstacles $\mathcal{O}_i^{\text{static}}$, and the vehicles' danger zones with respect to each other \mathcal{Z}_{ij} , our goal is, for each vehicle Q_i , to synthesize a controller which guarantees that Q_i reaches its target \mathcal{L}_i at or before the scheduled time of arrival t_i^{STA} , while avoiding the static obstacles $\mathcal{O}_i^{\text{static}}$ as well as the danger zones with respect to all other vehicles $\mathcal{Z}_{ij}, j \neq i$. In addition, we would like to obtain the latest departure time t_i^{LDT} such that Q_i can still arrive at \mathcal{L}_i on time.

In general, the above optimal path planning problem must be solved in the joint space of all N SPP vehicles. However, due to the high joint dimensionality, a direct dynamic

programming-based solution is intractable. Therefore, authors in [40] proposed to assign a priority to each vehicle, and perform SPP given the assigned priorities. Without loss of generality, let Q_j have a higher priority than Q_i if $j < i$. Under the SPP scheme, higher-priority vehicles can ignore the presence of lower-priority vehicles, and perform path planning without taking into account the lower-priority vehicles' danger zones. A lower-priority vehicle Q_i , on the other hand, must ensure that it does not enter the danger zones of the higher-priority vehicles $Q_j, j < i$; each higher-priority vehicle Q_j induces a set of time-varying obstacles $\mathcal{O}_i^j(t)$, which represents the possible states of Q_i such that a collision between Q_i and Q_j could occur.

It is straight-forward to see that if each vehicle Q_i is able to plan a trajectory that takes it to \mathcal{L}_i while avoiding the static obstacles $\mathcal{O}_i^{\text{static}}$ and the danger zones of *higher-priority vehicles* $Q_j, j < i$, then the set of SPP vehicles $Q_i, i = 1, \dots, N$ would all be able to reach their targets safely. Under the SPP scheme, path planning can be done sequentially in descending order of vehicle priority in the state space of only a single vehicle. Thus, SPP provides a solution whose complexity scales linearly with the number of vehicles, as opposed to exponentially with a direct application of dynamic programming approaches.

III. BACKGROUND

In this section, we present the basic SPP algorithm [40] in which disturbances are ignored and perfect information of vehicles positions is assumed. This simplification allows us to clearly present the basic SPP algorithm. However, in presence of disturbances, it is no longer possible to commit to exact trajectories (and hence positions), since the disturbance $d_i(\cdot)$ is *a priori* unknown. Thus, disturbances and incomplete information significantly complicate the SPP scheme. We next present the robust trajectory tracking algorithm [41] that can be used to make basic SPP approach robust to disturbances as well as to an imperfect knowledge of other vehicles' positions. All of these algorithms use time-varying reachability analysis to provide goal satisfaction and safety guarantees; therefore, we start with an overview of time-varying reachability.

A. Time-Varying Reachability Background

We will be using reachability analysis to compute a backward reachable set (BRS) \mathcal{V} given some target set \mathcal{L} , time-varying obstacle $\mathcal{G}(t)$, and the Hamiltonian function H which captures the system dynamics as well as the roles of the control and disturbance. The BRS \mathcal{V} in a time interval $[t, t_f]$ will be denoted by

$$\mathcal{V}(t, t_f) \quad (\text{backward reachable set}) \quad (3)$$

Several formulations of reachability are able to account for time-varying obstacles [29], [31] (or state constraints in general). For our application in SPP, we utilize the time-varying formulation in [31], which accounts for the time-varying nature of systems without requiring augmentation of the state space with the time variable. In the formulation in

[31], a BRS is computed by solving the following *final value* double-obstacle HJ VI:

$$\begin{aligned} \max \left\{ \min \{ D_t V(t, x) + H(t, x, \nabla V(t, x)), l(x) - V(t, x) \}, \right. \\ \left. -g(t, x) - V(t, x) \right\} = 0, \quad t \leq t_f \\ V(t_f, x) = \max \{ l(x), -g(t_f, x) \} \end{aligned} \quad (4)$$

In (4), the function $l(x)$ is the implicit surface function representing the target set $\mathcal{L} = \{x : l(x) \leq 0\}$. Similarly, the function $g(t, x)$ is the implicit surface function representing the time-varying obstacles $\mathcal{G}(t) = \{x : g(t, x) \leq 0\}$. The BRS $\mathcal{V}(t, t_f)$ is given by

$$\mathcal{V}(t, t_f) = \{x : V(t, x) \leq 0\} \quad (5)$$

Some of the reachability computations will not involve an obstacle set $\mathcal{G}(t)$, in which case we can simply set $g(t, x) \equiv \infty$ which effectively means that the outside maximum is ignored in (4).

The Hamiltonian, $H(t, x, \nabla V(t, x))$, depends on the system dynamics, and the role of control and disturbance. Whenever H does not depend explicit on t , we will drop the argument. In addition, the Hamiltonian is an optimization that produces the optimal control $u^*(t, x)$ and optimal disturbance $d^*(t, x)$, once V is determined. For BRSs, whenever the existence of a control (" $\exists u$ ") or disturbance is sought, the optimization is a minimum over the set of controls or disturbance. Whenever a BRS characterizes the behavior of the system for all controls (" $\forall u$ ") or disturbances, the optimization is a maximum. We will introduce precise definitions of reachable sets, expressions for the Hamiltonian, expressions for the optimal controls as needed for the many different reachability calculations we use.

B. SPP Without Disturbances and Intruder

In this section, we give an overview of the basic SPP algorithm assuming that there is no disturbance and intruder affecting the vehicles. Although in practice, such assumptions do not hold, the description of the basic SPP algorithm will introduce the notation needed for describing the subsequent, more realistic versions of SPP. The majority of the content in this section is taken from [40].

Recall that the SPP vehicles $Q_i, i = 1, \dots, N$, are each assigned a strict priority, with Q_j having a higher priority than Q_i if $j < i$. In the absence of disturbances, we can write the dynamics of the SPP vehicles as

$$\begin{aligned} \dot{x}_i &= f_i(x_i, u_i), t \leq t_i^{\text{STA}} \\ u_i &\in \mathcal{U}_i, \quad i = 1, \dots, N \end{aligned} \quad (6)$$

In SPP, each vehicle Q_i plans the path to its target set \mathcal{L}_i while avoiding static obstacles $\mathcal{O}_i^{\text{static}}$ and the obstacles $\mathcal{O}_i^j(t)$ induced by higher-priority vehicles $Q_j, j < i$. Path planning is done sequentially starting from the first vehicle and proceeding in descending priority, Q_1, Q_2, \dots, Q_N so that each of the path planning problems can be done in the state space of only one vehicle. During its path planning process, Q_i ignores the

presence of lower-priority vehicles $Q_k, k > i$, and induces the obstacles $\mathcal{O}_k^i(t)$ for $Q_k, k > i$.

From the perspective of Q_i , each of the higher-priority vehicles $Q_j, j < i$ induces a time-varying obstacle denoted $\mathcal{O}_i^j(t)$ that Q_i needs to avoid. Therefore, each vehicle Q_i must plan its path to \mathcal{L}_i while avoiding the union of all the induced obstacles as well as the static obstacles. Let $\mathcal{G}_i(t)$ be the union of all the obstacles that Q_i must avoid on its way to \mathcal{L}_i :

$$\mathcal{G}_i(t) = \mathcal{O}_i^{\text{static}} \cup \bigcup_{j=1}^{i-1} \mathcal{O}_i^j(t) \quad (7)$$

With full position information of higher priority vehicles, the obstacle induced for Q_i by Q_j is simply

$$\mathcal{O}_i^j(t) = \{x_i : \|p_i - p_j(t)\|_2 \leq R_c\} \quad (8)$$

Each higher priority vehicle Q_j plans its path while ignoring Q_i . Since path planning is done sequentially in descending order or priority, the vehicles $Q_j, j < i$ would have planned their paths before Q_i does. Thus, in the absence of disturbances, $p_j(t)$ is *a priori* known, and therefore $\mathcal{O}_i^j(t), j < i$ are known, deterministic moving obstacles, which means that $\mathcal{G}_i(t)$ is also known and deterministic. Therefore, the path planning problem for Q_i can be solved by first computing the BRS $\mathcal{V}_i^{\text{basic}}(t, t_i^{\text{STA}})$, defined as follows:

$$\begin{aligned} \mathcal{V}_i^{\text{basic}}(t, t_i^{\text{STA}}) = \{y : \exists u_i(\cdot) \in \mathbb{U}_i, x_i(\cdot) \text{ satisfies (23),} \\ \forall s \in [t, t_i^{\text{STA}}], x_i(s) \notin \mathcal{G}_i(s), \\ \exists s \in [t, t_i^{\text{STA}}], x_i(s) \in \mathcal{L}_i, x_i(t) = y\} \end{aligned} \quad (9)$$

The BRS $\mathcal{V}(t, t_i^{\text{STA}})$ can be obtained by solving (4) with $\mathcal{L} = \mathcal{L}_i$, $\mathcal{G}(t) = \mathcal{G}_i(t)$, and the Hamiltonian

$$H_i^{\text{basic}}(x_i, \lambda) = \min_{u_i \in \mathcal{U}_i} \lambda \cdot f_i(x_i, u_i) \quad (10)$$

The optimal control for reaching \mathcal{L}_i while avoiding $\mathcal{G}_i(t)$ is then given by

$$u_i^{\text{basic}}(t, x_i) = \arg \min_{u_i \in \mathcal{U}_i} \lambda \cdot f_i(x_i, u_i) \quad (11)$$

from which the trajectory $x_i(\cdot)$ can be computed by integrating the system dynamics, which in this case are given by (23). In addition, the latest departure time t_i^{LDT} can be obtained from the BRS $\mathcal{V}(t, t_i^{\text{STA}})$ as $t_i^{\text{LDT}} = \arg \sup_t \{x_i^0 \in \mathcal{V}(t, t_i^{\text{STA}})\}$. In summary, the basic SPP algorithm is given as follows:

Algorithm 1: Basic SPP algorithm: Suppose we are given initial conditions x_i^0 , vehicle dynamics (23), target sets \mathcal{L}_i , and static obstacles $\mathcal{O}_i^{\text{static}}, i = 1 \dots, N$. For each i in ascending order starting from $i = 1$ (which corresponds to descending order of priority),

- 1) determine the total obstacle set $\mathcal{G}_i(t)$, given in (18). In the case $i = 1$, $\mathcal{G}_i(t) = \mathcal{O}_i^{\text{static}} \forall t$;
- 2) compute the BRS $\mathcal{V}_i^{\text{basic}}(t, t_i^{\text{STA}})$ defined in (9). The latest departure time t_i^{LDT} is then given by $\arg \sup_t \{x_i^0 \in \mathcal{V}_i^{\text{basic}}(t, t_i^{\text{STA}})\}$;
- 3) determine the trajectory $x_i(\cdot)$ using vehicle dynamics (23), with the optimal control $u_i^{\text{basic}}(\cdot)$ given by (11);
- 4) given $x_i(\cdot)$, compute the induced obstacles $\mathcal{O}_k^i(t)$ for each $k > i$. In the absence of disturbances, $\mathcal{O}_k^i(t)$ is given by (8).

C. Robust Trajectory Tracking (RTT)

In the basic SPP algorithm, lower priority vehicles know the trajectories of all higher priority vehicles. The region that a lower priority vehicle needs to avoid is thus simply given by the danger zones around these trajectories; however, disturbances and incomplete information significantly complicate the SPP scheme. Committing to exact trajectories is no longer possible, since the disturbance $d_i(\cdot)$ is *a priori* unknown. Thus, the induced obstacles $\mathcal{O}_i^j(t)$ are no longer just the danger zones centered around positions. In this section, we provide an overview of the RTT algorithm that can overcome these issues. For simplicity of explanation, we will assume that no static obstacles exist, but method can be generalized even when static obstacles do exist. The material in this section is taken partially from [41]. Note that other algorithms have been developed in [41] to account for the disturbances, we use RTT algorithm for the simulations in this paper and only present RTT algorithm here. Interested readers are referred to [41] for the other algorithms.

Even though it is impossible to commit to and track an exact trajectory in the presence of disturbances, it may still be possible to instead *robustly* track a feasible *nominal* trajectory with a bounded error at all times. If this can be done, then the tracking error bound can be used to determine the induced obstacles. Here, computation is done in two phases: the *planning phase* and the *disturbance rejection phase*.

In the planning phase, a nominal trajectory $x_{r,j}(\cdot)$ is computed that is feasible in the absence of disturbances. This planning is done for a reduced control set $\mathcal{U}^p \subset \mathcal{U}$, as some margin is needed to reject unexpected disturbances while tracking the nominal trajectory.

In the disturbance rejection phase, we compute a bound on the tracking error, independently of the nominal trajectory. To compute this error bound, we find a robust controlled-invariant set in the joint state space of the vehicle and a tracking reference that may “maneuver” arbitrarily in the presence of an unknown bounded disturbance. Taking a worst-case approach, the tracking reference can be viewed as a virtual evader vehicle that is optimally avoiding the actual vehicle to enlarge the tracking error. We therefore can model trajectory tracking as a pursuit-evasion game in which the actual vehicle is playing against the coordinated worst-case action of the virtual vehicle and the disturbance.

Let x_j and $x_{r,j}$ denote the states of the actual vehicle Q_j and the virtual evader, respectively, and define the tracking error $e_j = x_j - x_{r,j}$. When the error dynamics are independent of the absolute state as in (12) (and also (7) in [27]), we can obtain error dynamics of the form

$$\begin{aligned} \dot{e}_j &= f_{e_j}(e_j, u_j, u_{r,j}, d_j), \\ u_j &\in \mathcal{U}_j, u_{r,j} \in \mathcal{U}_j^p, d_j \in \mathcal{D}_j, \quad t \leq 0 \end{aligned} \quad (12)$$

To obtain bounds on the tracking error, we first conservatively estimate the error bound around any reference state $x_{r,j}$, denoted \mathcal{E}_j :

$$\mathcal{E}_j = \{e_j : \|p_{e_j}\|_2 \leq R_{\text{EB}}\}, \quad (13)$$

where p_{e_j} denotes the position coordinates of e_j and R_{EB} is a design parameter. We next solve a reachability problem with its complement \mathcal{E}_j^c , the set of tracking errors violating the error bound, as the target in the space of the error dynamics. From \mathcal{E}_j^c , we compute the following BRS:

$$\begin{aligned} \mathcal{V}_j^{\text{EB}}(t, 0) = \{y : \forall u_j(\cdot) \in \mathbb{U}_j, \exists u_{r,j}(\cdot) \in \mathbb{U}_j^p, \exists d_j(\cdot) \in \mathbb{D}_i, \\ e_j(\cdot) \text{ satisfies (12), } e_j(t) = y, \\ \exists s \in [t, 0], e_j(s) \in \mathcal{E}_j^c\}, \end{aligned} \quad (14)$$

where the Hamiltonian to compute the BRS is given by:

$$H_j^{\text{EB}}(e_j, \lambda) = \max_{u_j \in \mathcal{U}_j} \min_{u_r \in \mathcal{U}_j^p, d_j \in \mathcal{D}_j} \lambda \cdot f_{e_j}(e_j, u_j, u_{r,j}, d_j). \quad (15)$$

Letting $t \rightarrow -\infty$, we obtain the infinite-horizon control-invariant set $\Omega_j := \lim_{t \rightarrow -\infty} (\mathcal{V}_j^{\text{EB}}(t, 0))^c$. If Ω_j is nonempty, then the tracking error e_j at flight time is guaranteed to remain within $\Omega_j \subseteq \mathcal{E}_j$ provided that the vehicle starts inside Ω_j and subsequently applies the feedback control law

$$\kappa_j(e_j) = \arg \max_{u_j \in \mathcal{U}_j} \min_{u_r \in \mathcal{U}_j^p, d_j \in \mathcal{D}_j} \lambda \cdot f_{e_j}(e_j, u_j, u_{r,j}, d_j). \quad (16)$$

The induced obstacles by each higher-priority vehicle Q_j can thus be obtained by:

$$\begin{aligned} \mathcal{O}_i^j(t) &= \{x_i : \exists y \in \mathcal{P}_j(t), \|p_i - y\|_2 \leq R_c\} \\ \mathcal{P}_j(t) &= \{p_j : \exists h_j, (p_j, h_j) \in \mathcal{M}_j(t)\} \\ \mathcal{M}_j(t) &= \Omega_j + x_{r,j}(t), \end{aligned} \quad (17)$$

where the “+” in (17) denotes the Minkowski sum¹. Intuitively, if Q_j is tracking $x_{r,j}(t)$, then it will remain within the error bound Ω_j around $x_{r,j}(t) \forall t$. This is precisely the set $\mathcal{P}_j(t)$. The induced obstacles can then be obtained by augmenting a danger zone around this set. Finally, we can obtain the total obstacle set $\mathcal{G}_i(t)$ using:

$$\mathcal{G}_i(t) = \mathcal{O}_i^{\text{static}} \cup \bigcup_{j=1}^{i-1} \mathcal{O}_i^j(t) \quad (18)$$

Since each vehicle Q_j , $j < i$, can only be guaranteed to stay within Ω_j , we must make sure during the path planning of Q_i that at any given time, the error bounds of Q_i and Q_j , Ω_i and Ω_j , do not intersect. This can be done by augmenting the total obstacle set by Ω_i :

$$\tilde{\mathcal{G}}_i(t) = \mathcal{G}_i(t) + \Omega_i. \quad (19)$$

Finally, given Ω_i , we can guarantee that Q_i will reach its target \mathcal{L}_i if $\Omega_i \subseteq \mathcal{L}_i$; thus, in the path planning phase, we modify \mathcal{L}_i to be $\tilde{\mathcal{L}}_i := \{x_i : \Omega_i + x_i \subseteq \mathcal{L}_i\}$, and compute a BRS, with the control authority \mathcal{U}_i^p , that contains the initial state of the vehicle. Mathematically,

$$\begin{aligned} \mathcal{V}_i^{\text{rtt}}(t, t_i^{\text{STA}}) = \{y : \exists u_i(\cdot) \in \mathbb{U}_i^p, x_i(\cdot) \text{ satisfies (23),} \\ \forall s \in [t, t_i^{\text{STA}}], x_i(s) \notin \tilde{\mathcal{G}}_i(t), \\ \exists s \in [t, t_i^{\text{STA}}], x_i(s) \in \tilde{\mathcal{L}}_i, x_i(t) = y\} \end{aligned} \quad (20)$$

¹The Minkowski sum of sets A and B is the set of all points that are the sum of any point in A and B .

The BRS $\mathcal{V}_i^{\text{rtt}}(t, t_i^{\text{STA}})$ can be obtained by solving (4) using the Hamiltonian:

$$H_i^{\text{rtt}}(x_i, \lambda) = \min_{u_i \in \mathcal{U}_i^p} \lambda \cdot f_i(x_i, u_i) \quad (21)$$

The corresponding optimal control for reaching $\tilde{\mathcal{L}}_i$ is given by:

$$u_i^{\text{rtt}}(t) = \arg \min_{u_i \in \mathcal{U}_i^p} \lambda \cdot f_i(x_i, u_i). \quad (22)$$

The nominal trajectory $x_{r,i}(\cdot)$ can thus be obtained by using vehicle dynamics in the absence of disturbances

$$\begin{aligned} \dot{x}_i &= f_i(x_i, u_i), t \leq t_i^{\text{STA}} \\ u_i &\in \mathcal{U}_i, \quad i = 1 \dots, N, \end{aligned} \quad (23)$$

with the optimal control $u_i^{\text{rtt}}(\cdot)$ given by (22). From the resulting nominal trajectory $x_{r,i}(\cdot)$, the overall control policy to reach \mathcal{L}_i can be obtained via (16). The robust trajectory tracking method can be summarized as follows:

Algorithm 2: Robust trajectory tracking algorithm: Given initial conditions x_i^0 , vehicle dynamics (1), target sets \mathcal{L}_i , and static obstacles $\mathcal{O}_i^{\text{static}}, i = 1 \dots, N$, for each i ,

- 1) determine the total obstacle set $\mathcal{G}_i(t)$, given in (18). In the case $i = 1$, $\mathcal{G}_i(t) = \mathcal{O}_i^{\text{static}} \forall t$;
- 2) decide on a reduced control authority \mathcal{U}_i^p for the planning phase, and choose a parameter R_{EB} to conservatively bound the tracking error;
- 3) compute the BRS $\mathcal{V}_i^{\text{EB}}(t, 0)$ using (14) and make sure that $\Omega_i \neq \emptyset$. Given R_{EB} , the error bound on the tracking error is given by Ω_i ;
- 4) using Ω_i , determine the augmented obstacle set $\tilde{\mathcal{G}}_i(t)$, given in (19);
- 5) compute the BRS $\mathcal{V}_i^{\text{rtt}}(t, t_i^{\text{STA}})$ as described in (20) using the reduced target set $\tilde{\mathcal{L}}_i$, $\tilde{\mathcal{G}}_i(t)$ as obstacles, and the control authority \mathcal{U}_i^p . The latest departure time t_i^{LDT} is then given by $\arg \sup_t x_i^0 \in \mathcal{V}_i^{\text{rtt}}(t, t_i^{\text{STA}})$;
- 6) compute the nominal trajectory $x_{r,i}(\cdot)$ for Q_i in the absence of disturbances, which can be obtained using the vehicle dynamics in (23) and the optimal control given in (22);
- 7) the induced obstacles $\mathcal{O}_i^k(t)$ for each $k > i$ can be computed using Ω_i and $x_{r,i}(\cdot)$ via (17).

IV. CITY ENVIRONMENT SIMULATION

We now illustrate SPP algorithm using a fifty-vehicle UAV system where UAVs are flying through a city environment. This setup can be representative of many UAV applications, such as package delivery, aerial surveillance, etc.

A. Setup

We grid San Francisco (SF) city in California, US and use it as our state space, as shown in Figure 1.

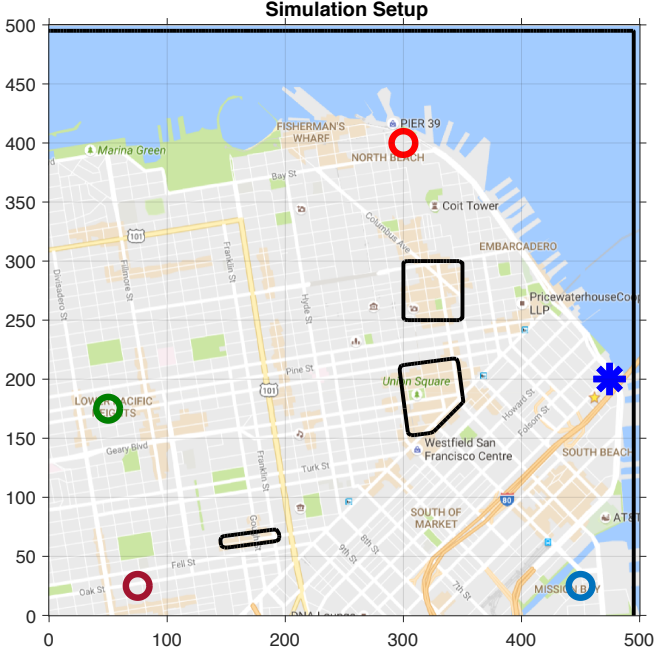


Fig. 1: Simulation setup. A 25km^2 area of San Francisco city is used as the state-space for vehicles. SPP vehicles originate from the Blue star and go to one of the four destinations, denoted by circles. Tall buildings in the downtown area are used as static obstacles, represented by the black contours.

Each box in Figure 1 represents a $500\text{m} \times 500\text{m}$ area of SF. The origin point for the vehicles is denoted by the Blue star. Four different areas in the city are chosen as the destinations for the vehicles. Mathematically, the target sets \mathcal{L}_i of the vehicles are circles of radius r in the position space, i.e. each vehicle is trying to reach some desired set of positions. In terms of the state space x_i , the target sets are defined as

$$\mathcal{L}_i = \{x_i : \|p_i - c_i\|_2 \leq r\} \quad (24)$$

where c_i are centers of the target circles. In this simulation, we use $r = 100\text{m}$. The four targets are represented by four circles in Figure 1. The destination of each vehicle is chosen randomly from these four destinations. Finally, tall buildings in downtown San Francisco are used as static obstacles for the SPP vehicles, denoted by black contours in Figure 1.

For this simulation, we use the following dynamics for each vehicle:

$$\begin{aligned} \dot{p}_{x,i} &= v_i \cos \theta_i + d_{x,i} \\ \dot{p}_{y,i} &= v_i \sin \theta_i + d_{y,i} \\ \dot{\theta}_i &= \omega_i, \\ \underline{v} &\leq v_i \leq \bar{v}, |\omega_i| \leq \bar{\omega}, \|(d_{x,i}, d_{y,i})\|_2 \leq d_r, \end{aligned} \quad (25)$$

where $x_i = (p_{x,i}, p_{y,i}, \theta_i)$ is the state of vehicle Q_i , $p_i = (p_{x,i}, p_{y,i})$ is the position, θ_i is the heading, and $d = (d_{x,i}, d_{y,i})$ represents Q_i 's disturbances, for example wind, that affect its position evolution. The control of Q_i is $u_i = (v_i, \omega_i)$, where v_i is the speed of Q_i and ω_i is the turn rate; both controls have a lower and upper bound. To make our simulations as close as possible to real scenarios, we choose velocity and turn-rate bounds as $\underline{v} = 0\text{m/s}$, $\bar{v} = 25\text{m/s}$, $\bar{\omega} =$

2rad/s , aligned with the modern UAV specs [43], [44]. The disturbance bound is chosen as $d_r = 6\text{m/s}$, which corresponds to *moderate winds* on Beaufort wind force scale [45]. Note that we have used same dynamics and input bounds across all vehicles for clarity of illustration; however, SPP can easily handle more general systems of the form in which the vehicles have different control bounds and dynamics.

The goal of the vehicles is to reach their destinations while avoiding a collision with the other vehicles or the static obstacles. The joint state space of this fifty-vehicle system is 150-dimensional (150D), making the joint path planning and collision avoidance problem intractable for direct analysis using HJ reachability. Therefore, we assign a priority order to vehicles and solve the path planning problem sequentially. For this simulation, we assign a random priority order to fifty vehicles and use RTT algorithm to compute the trajectories of the vehicles.

B. Results

Focus on the following aspects:

- The technical details for the simulations, like RTT parameters, relative co-ordinate dynamics, rotation and translation of obstacles, union for obstacles, etc.
- Demonstration of theory (the vehicles avoid collision w/ other vehicles and reach their destinations).
- Scaling of SPP.
- Provide some more intuition about the solution that emerge out of theory– Space-time separation, type of space-time trajectories (Almost straight line path w/ different starting times?), etc.
- Reactivity of controller to the actual disturbance (Claire: be very detailed about explaining the setup of simulation)
- Illustrate how the type of space-time trajectories change with change in disturbance bounds and STA

REFERENCES

- [1] B. P. Tice, “Unmanned Aerial Vehicles – The Force Multiplier of the 1990s,” *Airpower Journal*, 1991.
- [2] W. DeBusk, “Unmanned Aerial Vehicle Systems for Disaster Relief: Tornado Alley,” in *AIAA Infotech@Aerospace 2010*. American Institute of Aeronautics and Astronautics, Apr. 2010, pp. 2010–3506.
- [3] Amazon.com, Inc., “Amazon Prime Air,” 2016. [Online]. Available: <http://www.amazon.com/b?node=8037720011>
- [4] AUVSI News, “UAS Aid in South Carolina Tornado Investigation,” 2016. [Online]. Available: <http://www.auvsi.org/blogs/auvsi-news/2016/01/29/tornado>
- [5] BBC Technology, “Google plans drone delivery service for 2017,” 2016. [Online]. Available: <http://www.bbc.com/news/technology-34704868>
- [6] Joint Planning and Development Office, “Unmanned Aircraft Systems (UAS) Comprehensive Plan,” Federal Aviation Administration, Tech. Rep., 2014.
- [7] T. Prevot, J. Rios, P. Kopardekar, J. E. Robinson III, M. Johnson, and J. Jung, “UAS Traffic Management (UTM) Concept of Operations to Safely Enable Low Altitude Flight Operations,” in *16th AIAA Aviation Technology, Integration, and Operations Conference*. American Institute of Aeronautics and Astronautics, Jun. 2016, pp. 1–16.
- [8] P. Fiorini and Z. Shiller, “Motion Planning in Dynamic Environments Using Velocity Obstacles,” *The International Journal of Robotics Research*, vol. 17, no. 7, pp. 760–772, Jul. 1998.
- [9] G. Chasparis and J. Shamma, “Linear-programming-based multi-vehicle path planning with adversaries,” in *American Control Conference*, Jun. 2005, pp. 1072–1077.

- [10] J. van den Berg, Ming Lin, and D. Manocha, "Reciprocal Velocity Obstacles for real-time multi-agent navigation," in *International Conference on Robotics and Automation*, May 2008, pp. 1928–1935.
- [11] A. Wu and J. P. How, "Guaranteed infinite horizon avoidance of unpredictable, dynamically constrained obstacles," *Autonomous Robots*, vol. 32, no. 3, pp. 227–242, Apr. 2012.
- [12] R. Olfati-Saber and R. M. Murray, "DISTRIBUTED COOPERATIVE CONTROL OF MULTIPLE VEHICLE FORMATIONS USING STRUCTURAL POTENTIAL FUNCTIONS," *IFAC Proceedings Volumes*, vol. 35, no. 1, pp. 495–500, 2002.
- [13] Y. L. Chuang, Y. R. Huang, M. R. D'Orsogna, and A. L. Bertozzi, "Multi-vehicle flocking: Scalability of cooperative control algorithms using pairwise potentials," in *International Conference on Robotics and Automation*, Apr. 2007, pp. 2292–2299.
- [14] Feng-Li Lian and R. Murray, "Real-time trajectory generation for the cooperative path planning of multi-vehicle systems," in *Conference on Decision and Control*, vol. 4, Dec. 2002, pp. 3766–3769.
- [15] A. Ahmadzadeh, N. Motee, A. Jadbabaie, and G. Pappas, "Multi-vehicle path planning in dynamically changing environments," in *International Conference on Robotics and Automation*, May 2009, pp. 2449–2454.
- [16] J. Bellingham, M. Tillerson, M. Alighanbari, and J. How, "Cooperative path planning for multiple UAVs in dynamic and uncertain environments," in *Conference on Decision and Control*, vol. 3, Dec. 2002, pp. 2816–2822.
- [17] R. Beard and T. McLain, "Multiple UAV cooperative search under collision avoidance and limited range communication constraints," in *Conference on Decision and Control*, vol. 1, 2003, pp. 25–30.
- [18] T. Schouwenaars and E. Feron, "Decentralized Cooperative Trajectory Planning of Multiple Aircraft with Hard Safety Guarantees," in *Guidance, Navigation, and Control Conference and Exhibit*, Aug. 2004, pp. 2004–5141.
- [19] D. M. Stipanovic, P. F. Hokayem, M. W. Spong, and D. D. Siljak, "Cooperative Avoidance Control for Multiagent Systems," *Journal of Dynamic Systems, Measurement, and Control*, vol. 129, no. 5, p. 699, 2007.
- [20] M. Massink and N. De Francesco, "Modelling free flight with collision avoidance," in *International Conference on Engineering of Complex Computer Systems*, 2001, pp. 270–279.
- [21] M. Althoff and J. M. Dolan, "Set-based computation of vehicle behaviors for the online verification of autonomous vehicles," in *International Conference on Intelligent Transportation Systems*, Oct. 2011, pp. 1162–1167.
- [22] Y. Lin and S. Saripalli, "Collision avoidance for UAVs using reachable sets," in *International Conference on Unmanned Aircraft Systems*, Jun. 2015, pp. 226–235.
- [23] E. Lalish, K. A. Morgansen, and T. Tsukamaki, "Decentralized reactive collision avoidance for multiple unicycle-type vehicles," in *American Control Conference*, Jun. 2008, pp. 5055–5061.
- [24] G. M. Hoffmann and C. J. Tomlin, "Decentralized cooperative collision avoidance for acceleration constrained vehicles," in *Conference on Decision and Control*, 2008, pp. 4357–4363.
- [25] M. Chen, C.-Y. Shih, and C. J. Tomlin, "Multi-Vehicle Collision Avoidance via Hamilton-Jacobi Reachability and Mixed Integer Programming," in *Conference on Decision and Control (to appear)*, 2016.
- [26] E. N. Barron, "Differential games with maximum cost," *Nonlinear Analysis*, vol. 14, no. 11, pp. 971–989, Jun. 1990.
- [27] I. Mitchell, A. Bayen, and C. Tomlin, "A time-dependent Hamilton-Jacobi formulation of reachable sets for continuous dynamic games," *Transactions on Automatic Control*, vol. 50, no. 7, pp. 947–957, Jul. 2005.
- [28] O. Bokanowski, N. Forcadell, and H. Zidani, "Reachability and Minimal Times for State Constrained Nonlinear Problems without Any Controllability Assumption," *Journal on Control and Optimization*, vol. 48, no. 7, pp. 4292–4316, Jan. 2010.
- [29] O. Bokanowski and H. Zidani, "MINIMAL TIME PROBLEMS WITH MOVING TARGETS AND OBSTACLES," *IFAC Proceedings Volumes*, vol. 44, no. 1, pp. 2589–2593, Jan. 2011.
- [30] K. Margellos and J. Lygeros, "HamiltonJacobi Formulation for ReachAvoid Differential Games," *Transactions on Automatic Control*, vol. 56, no. 8, pp. 1849–1861, Aug. 2011.
- [31] J. F. Fisac, M. , C. J. Tomlin, and S. S. Sastry, "Reach-avoid problems with time-varying dynamics, targets and constraints," in *International Conference on Hybrid Systems Computation and Control*, 2015, pp. 11–20.
- [32] J. A. Sethian, "A fast marching level set method for monotonically advancing fronts," *National Academy of Sciences*, vol. 93, no. 4, pp. 1591–1595, Feb. 1996.
- [33] S. Osher and R. Fedkiw, *Level Set Methods and Dynamic Implicit Surfaces*. Springer-Verlag, 2006.
- [34] I. M. Mitchell, "Application of Level Set Methods to Control and Reachability Problems in Continuous and Hybrid Systems," Ph.D. dissertation, Stanford University, 2002.
- [35] "A toolbox of level set methods," Tech. Rep., 2007.
- [36] A. M. Bayen, I. M. Mitchell, M. K. Osihi, and C. J. Tomlin, "Aircraft Autolander Safety Analysis Through Optimal Control-Based Reach Set Computation," *Journal of Guidance, Control, and Dynamics*, vol. 30, no. 1, pp. 68–77, Jan. 2007.
- [37] J. Ding, J. Sprinkle, S. S. Sastry, and C. J. Tomlin, "Reachability calculations for automated aerial refueling," in *Conference on Decision and Control*, 2008, pp. 3706–3712.
- [38] P. Bouffard, "On-board model predictive control of a quadrotor helicopter: Design, implementation, and experiments," Master's thesis, University of California, Berkeley, 2012.
- [39] H. Huang, J. Ding, W. Zhang, and C. J. Tomlin, "A differential game approach to planning in adversarial scenarios: A case study on capture-the-flag," in *International Conference on Robotics and Automation*, 2011, pp. 1451–1456.
- [40] M. Chen, J. F. Fisac, S. Sastry, and C. J. Tomlin, "Safe sequential path planning of multi-vehicle systems via double-obstacle Hamilton-Jacobi-Isaacs variational inequality," in *European Control Conference*, Jul. 2015, pp. 3304–3309.
- [41] S. Bansal, M. Chen, J. F. Fisac, and C. J. Tomlin, "Safe Sequential Path Planning of Multi-Vehicle Systems Under Presence of Disturbances and Imperfect Information," in *American Control Conference (To appear)*, 2017.
- [42] M. Chen, S. Bansal, J. F. Fisac, and C. J. Tomlin, "Robust sequential path planning under disturbances and adversarial intruder," *arXiv preprint arXiv:1611.08364*, 2016.
- [43] 3D Robotics, "Solo Specs: Just the facts," 2015. [Online]. Available: <https://news.3dr.com/solo-specs-just-the-facts-14480cb55722#.w7057q926>
- [44] New Atlas, "Amazon Prime Air." [Online]. Available: <http://newatlas.com/amazon-new-delivery-drones-us-faa-approval/36957/>
- [45] Wikipedia, "Beaufort scale." [Online]. Available: https://en.wikipedia.org/wiki/Beaufort_scale#Modern_scale