

Airspace Management of Autonomous UAVs

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1. INTRODUCTION

One major issue currently preventing the adoption of autonomous unmanned air vehicles (UAVs) is the lack of airspace management to prevent the UAVs from colliding with each other, with human-piloted planes or helicopters, with static objects such as buildings, and with dynamic flying objects such as flocks of birds. In this work, we present a novel airspace management approach to autonomous UAVs. Our airspace management system allows UAVs to dynamically and autonomously choose between three modes of operation: (i) centralized, (ii) cooperative decentralized, (iii) noncooperative decentralized.

Centralized mode of operation: The UAV delegates the collision avoidance responsibilities to an airspace management center. This center detects potential collisions between the UAV and other objects in the airspace and suggests that the UAV take a new course.

Cooperative decentralized mode of operation: The UAV detects a possible collision with another object in the airspace and communicates with that object to solve the conflict if the object is cooperative. If the other object does not cooperate, the UAV acts the same way as in the noncooperative decentralized mode of operation.

Noncooperative decentralized mode of operation: The UAV detects a possible collision with another object in the airspace and diverts itself without using any communication means.

While the airspace management center holds global information, each UAV holds partial information about the trajectories of neighboring bodies. It updates its knowledge base regularly, using available means such as the airspace management center, bilateral cooperation protocols, and on-board sensors.

In this demonstration, we have setup a number of UAVS

¹This demonstration is a live demo software.

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flying over an area. As a pilot, you will fly in the fly zone allocated to the UAVs for your mission. The responsibility of our airspace management system is to prevent collision between any manned aircraft and the UAVs at cost.

2. DEMONSTRATING STATIONS

To demonstrate our solution we introduce the following stations. Each station is a computer that includes a communication line and software that simulates the behavior of the represented entity.

(i) **Airspace monitoring stations.** Each monitoring station graphically presents an overview of the current state of entities, such as UAVs, aircraft, and buildings. Each flying object includes a display of its past trail along with its projected future path. The airspace monitoring station is updated each second to reflect the current state of the entities residing within the monitored airspace.

The user can navigate through the airspace to inspect the dynamically changed environment, and to learn about possible collisions and how they can be avoided. The airspace monitoring station is a web-based application. It uses *Google Earth* infrastructure and is publicly available to use online during the conference from every computer connected to the Internet.

(ii) **UAV control stations.** Each control station represents a specific UAV. The station graphically presents the environmental perception of the UAV such as sensed nearby objects, its resource availability, and its current mode of operation.

The user can visually see the airspace from the UAV point of view and may control its resources. By changing the state of the UAV resources, the user influences the mode of operation. Therefore, upon changing the state of the resources, the user might see a new UAV behavior.

(iii) **Aircraft control stations.** Each aircraft control station represents a specific passenger airplane in the airspace. The station graphically presents the nearby airspace information from the airplane point of view.

From this station, the user can control the maneuvers of the plane by using a joystick. During the demo session, each user can try to deliberately collide with UAVs to see how these UAVs avoid collisions.

3. CONFLICT DETECTION AND AVOIDANCE

In our airspace management system we propose to use two types of agents. The UAV agent controls the behavior of a UAV such that each UAV includes an agent instructing it how to avoid collisions and what path to follow to achieve its

mission. The other type, named the *centralized agent*, controls the behavior of the command and control center. This agent instructs all UAV agents on how to avoid collisions and what path to follow in order to achieve their missions. While UAV agents have only partial information about their environment, the centralized agent has full knowledge about the problem space.

We use *UAV path* functions to describe the state of each UAV at a given time. Intersection between two UAVs happens when two UAVs are very close (less than 1 m) to each other at a given time. The following definitions formalize this notation:

Definition 1. Let A be a set of n UAV agents such that $A = \bigcup_{i \in N} a_i$ whereas $N = \{0, 1, \dots, n-1\}$.

Definition 2. Let time period t be a singular point in the time dimension T such that $t \in T$.

Definition 3. Let state s be an agent state describing its location at a given time t . Let S be a set of possible agent states such that $s \in S$.

Definition 4. Let UAV path $P_{a_i, t_0, t_1}(t)$ be an agent state function that associates a state with agent a_i over time from t_0 to t_1 .

Definition 5. Let $d_{s_i, s_j}(t)$ be the distance between the states of a_i and a_j at a given time t whereas $s_i = P_{a_i, t_0, t_1}(t)$, $s_j = P_{a_j, t'_0, t'_1}(t)$, $t_0 \leq t \leq t_1$, and $t'_0 \leq t \leq t'_1$.

Definition 6. Let intersection $I_{a_i, a_j, t_{int}}$ be an event in time t_{int} related to agents a_i and a_j such that $d_{s_i, s_j}(t_{int}) \leq \theta$ where θ is the intersection range.

Definition 7. Let collision C_{a_i, a_j} be an intersection $I_{a_i, a_j, t_{int}}$ while $t_{int} = \tau$ and τ is the current time.

Our path modification algorithm works within the four dimensions (x,y,z and time), which means it can create a conflict-free zone by changing the path or simply by changing the speed of a UAV. Path detour of agent a_i is computed in the following way:

Given the time of intersection t_{int} a new state s_i^* is computed using the state at the time of intersection, such that $s_i^* = P_{a_i, t_0, t_1}(t_{int})$ while $t_0 \leq t_{int} \leq t_1$. We then produce a new path P^* that is a combination of the former path P and a detour path P' . The detour path extends a path from time t_s to time t_e such that $t_0 \leq t_s \leq t_{int} \leq t_e \leq t_1$ passing through s_i^* at time t_{int} . We use the original path from t_0 to t_s and from t_e to t_1 . We then validate the new path. If the new path does not solve the intersection we repeat the process. To minimize the diversion from the original course we relate the detour interval $t_s..t_e$ to the number of iterations. We increase the detour interval with the number of iterations to increase the probability of finding a solution at the expense of extended detour.

4. STORYBOARD

Over San Francisco, we are deploying nine UAVs with intersecting paths. The first task of the airspace management system is to produce conflict-free paths so that the UAVs do not collide. In an *airspace monitoring station* we may see in red the original path of each UAV and in yellow the deconflicted path. The UAVs are following their paths, when a

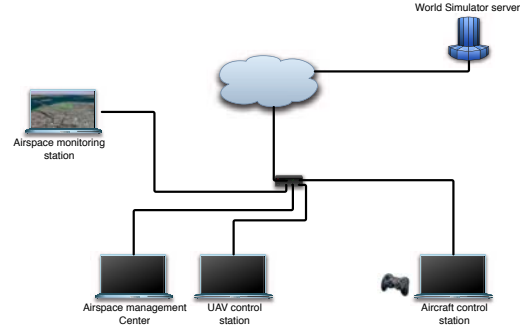


Figure 1: System setup system

manned aircraft, marked in green, using an *aircraft control station* is entering the airspace. The manned aircraft does not have an a priori path, so the airspace management center and each UAV make sure that, whatever the pilot does, no collision is possible. Note that even though the original paths of the UAVs and the human-controlled plane collide, the resulting behavior affects only the UAVs.