Feasibility and performance benefits of directional force fields for the tactical conflict management of UAVs

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Abstract. As we move towards scenarios where the adoption of unmanned aerial vehicles (UAVs) becomes massive, smart solutions are required to efficiently solve conflicts in the flight trajectories of aircraft so as to avoid potential collisions. Among the different possible approaches, adopting virtual force fields is a possible solution acknowledged for being simple, distributed, and yet effective. In this paper, we study the feasibility of a directional force field (D-FFP) approach, preliminary assessing its performance benefits compared to a standard force field protocol (FFP) using Matlab simulation. Results show that, in typical scenarios associated with aerial traffic corridors, the proposed approach can reduce the flight time overhead by 32% (on average) while maintaining the required flight safety distances between aircraft.

Keywords: UAV · Tactical conflict management · Field force · Collision avoidance.

1 Introduction

The emerging Smart City paradigm is fostering developments in several research areas, including air transportation. In particular, the airspace of future cities is expected to be crowded with different aircraft performing all sorts of activities [9]. To meet this challenge, different initiatives, like U-Space [2] in Europe, attempt to regulate and standardize aerial operations so as to promote safety and efficiency.

When addressing conflicts between different aircraft in certain controlled airspace, two complementary approaches are usually considered [3]: (i) strategic conflict management, whereby possible conflicts are detected and handled before the UAVs take off by analyzing the specified flight plans, and proposing modifications to those plans if potential conflicts are detected; and (ii) tactical conflict management, which consists of managing conflicts dynamically once the UAVs are in flight. Concerning the latter, different approaches can be found in the literature [13]. Among them, force-field methods are popular for their simplicity in terms of logic and implementation, while allowing to seamlessly

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scale to any number of obstacles/vehicles. Yet, they require precise tuning and thorough validation to address possible instability issues.

In a previous work [12] we presented FFP, a Force-Field protocol targeting UAVs of the multirotor type, that is able to achieve good performance in different realistic types of aerial conflicts while outperforming a geometric protocol [6]. Yet, simulation results have shown that there is still a margin for improvement. Hence, in this paper, we explore a novel (yet more complex) approach by introducing directional force fields. Preliminary experiments performed in the Matlab environment highlight the potential benefits of this new technique, showing performance improvements over the legacy FFP technique.

The remainder of the paper is organized as follows: in the next section, we provide a brief overview of some related works. Then, in section 3, we make an overview of our proposed solution. Section 4 details how experiments were defined, and the main performance results achieved. Finally, section 5 presents the main conclusions of this work, also discussing future work.

2 Related works

The field of collision avoidance systems (CAS) has been extensively studied for all types of vehicles. Various types of solutions exist, and a good classification of these approaches can be found in [13].

An analysis of the literature shows that there are only a few works (considering UAVs) that use a force-field approach to avoid collisions. Most of them are only considering static obstacles [10, 11, 1, 7]. In the work of [4] Choi et al., both static and moving obstacles were taken into account. Using a curl-free vector field, they were able to avoid the obstacles successfully. Their work was especially focused on solving the local minimum problem that exists for static obstacles. Furthermore, Kownacki et al. [8], also used a force-field approach to avoid collisions. In their work, they considered nonholonomic UAVs (e.g. fixed-wing planes) with several numerical simulations showing the validity of their algorithm. All the abovementioned works were tested in simulation, and MATLAB was often used. With this type of simulation, many experiments can be performed rather quickly, which is adequate for preliminary works. However, it often omits many physical intricacies (e.g. inertia). Therefore, in a previous work (FFP) [12], we implemented a force-field approach that showed how collisions could be avoided with only a small time overhead. However, in that approach, we did not take the direction of the obstacle w.r.t the flying direction into account. That is, the magnitude of the repulsion vector had the same size independently whether the obstacle was right in front of the UAV or on the side. This made the UAVs repel some obstacles stronger than necessary. Hence, in this paper, we make a preliminary assessment of a directional force field protocol (D-FFP), as detailed below.

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3 Proposed solution

The original FFP protocol [12] uses a conventional approach whereby the flight destination is modeled as a constant attraction force, emulating a gravitational field. Instead, the repulsion between UAVs is modeled following the principles of repulsion between two similar electrical charges, having the properties of (i) being omnidirectional, and (ii) experiencing a decay of intensity with distance. In this paper, we propose a different repulsion model that is instead inspired by the repulsion properties between two magnets with the same polarity, meaning that the repulsion force depends on direction (θ). This behavior has been modeled according to the following equation:

$$R(\theta, \mu) = \begin{cases} \cos(\mu \cdot \theta) : \theta \in [-\frac{\pi}{2 \cdot \mu}, \frac{\pi}{2 \cdot \mu}] \\ C : \theta \notin [-\frac{\pi}{2 \cdot \mu}, \frac{\pi}{2 \cdot \mu}] \end{cases} \tag{1}$$

In this equation, we can modulate the repulsion behavior by adjusting parameters C and μ, whereby C is a constant value in the range between 0 and 1, which determines how large the omnidirectional component of the force field is, while μ allows regulating how narrow is the main lobe.

Figure 1 shows the resulting repulsion pattern generated when setting C to 0.25, and μ to 2, values which we will use for the experiments that will follow. We can see that, for angles close to zero (target along the line defined by the speed vector), repulsion values are very high, being reduced as we move away from that reference direction until reaching a minimum constant repulsion value, which applies for most other directions. Finally, as in the FFP protocol, the resulting direction vector is obtained using the attraction force, and the repulsion force (the latter being determined by equation 1).

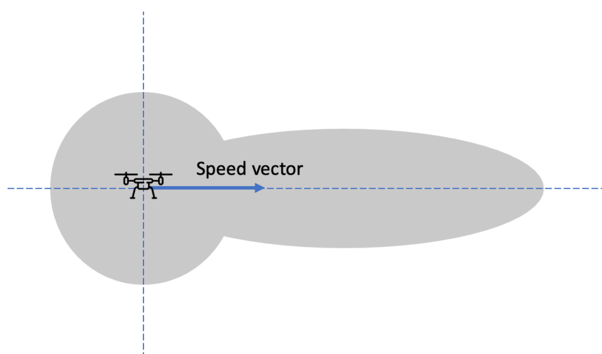

Fig. 1: Generated repulsion pattern ($C = 0.25; \mu = 2$).

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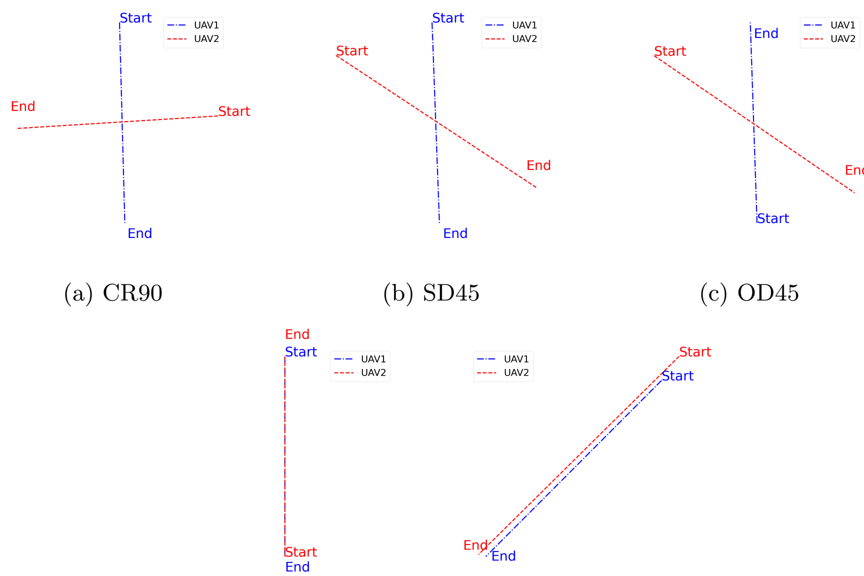

(a) CR90 (b) SD45 (c) OD45

(d) HO (e) TO

Fig. 2: Overview of the five test scenarios.

4 Simulation results

In this section, we perform some experiments to validate the D-FFP proposal, while evaluating to which extent the proposed solution is able to improve upon the conventional FFP solution. To achieve this, we first detail how the reference simulation experiments were defined, and afterwards, we present some preliminary performance results, with discussion.

4.1 Simulation setup

To perform our experiments, we implemented both FFP and D-FFP in Matlab and simulated the dynamics of two UAV trajectories. For performance assessment purposes, we have devised five representative scenarios whereby two UAVs have intersecting trajectories; the purpose is to provoke a conflict that must be addressed by the collision avoidance protocols. These five scenarios are shown in figure 2.

In terms of performance metrics, what is sought is an optimal trade-off between the flight time overhead introduced and the safety distance between UAVs. Hence, we will measure the UAVs' total flight time (TFT) to compare the time differences between both protocols. In addition, we will also measure the minimum distance between UAVs that was registered in the experiment. We

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should keep in mind that a minimum of 10 meters of separation between them should be maintained to account for GPS error ($\pm 5m$ for each).

4.2 Performance analysis

We now present the performance results obtained in the five scenarios described above. These results are summarized in table 1. We measured the performance using two different metrics: (i) the minimal distance between the UAVs and (ii) the time overhead (TO) introduced by our algorithm. For the time overhead, we compare the executing time with the minimal time required to finish the mission, i.e. when no collision avoidance algorithm is applied. As we can observe from table 1, our new D-FFP algorithm does decrease the time overhead in all cases. On average, the time overhead is reduced by 8 seconds, which is a 32% reduction compared to the previous FFP algorithm. Notice that these gains are achieved while respecting the safety distance of 10 meters between aircraft, as desired.

Table 1: Performance results for the 5 different scenarios under test when comparing the FFP and D-FFP protocols in terms of the minimum distance between UAVs and time overhead (TO) w.r.t the minimal time.

Scenario	Min. T. [s]	**FFP**		**D-FFP**	
		TO [s]	**Min. distance [m]**	**TO[s]**	**Min. distance [m]**
CR90	84.47	34.90	16.10	26.46	10.86
SD45	81.91	42.15	10.87	30.99	10.00
OD45	80.70	24.53	20.62	16.50	14.56
HO	83.04	16.82	10.81	8.38	11.81
TO	233.31	5.57	11.70	1.57	10.26
Average	***112.69***	***24.80***	***14.02***	***16.78***	***11.50***

To gain further insight into how such improvements are achieved, in figure 3 we show the actual trajectories for the two conflicting UAVs in the OD45 scenario. As shown, the adoption of D-FFP achieves a more efficient and clean avoidance trajectory, which reduces the flight time of both UAVs by reducing trajectory fluctuations. On the contrary, the FFP trajectories are slightly irregular, and sometimes the drones go around in circles, waiting to pass.

5 Conclusions and future work

In this paper, we have proposed a novel field-force approach to improve airspace management in the presence of conflicts between aircraft. In particular, we improve upon conventional field-force approaches, which assume an omnidirectional repulsion pattern around each UAV, by introducing a directional repulsion pattern.

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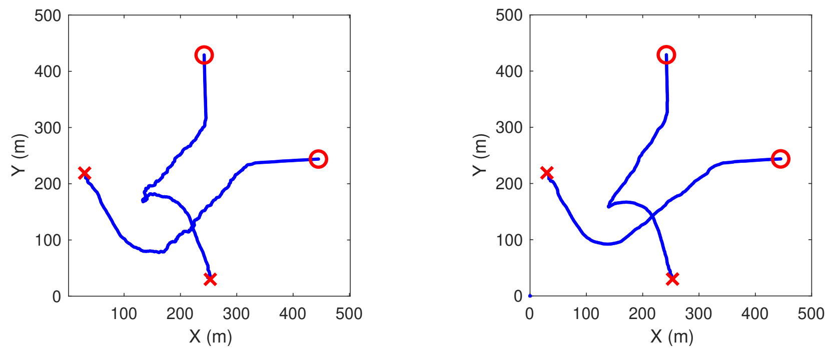

(a) FFP (b) D-FFP

Fig. 3: UAV flight trajectories for both protocols under test.

Preliminary experiments using Matlab simulation evidence the potential of the proposed technique, which is able to improve upon the conventional approach by reducing the overall time overhead associated with collision avoidance manoeuvres, while always guaranteeing the safety distance between UAVs.

As future work, we first plan to further study the potential of this solution by analyzing the impact of the different design alternatives available while seeking the most optimal combination of parameters in terms of performance. An extension to 3D manoeuvring is also planned. We also plan to evaluate the algorithms using more real simulators such as the ArduSim [5] and, finally, the idea is to implement and test it using real drones.

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