Biologically-inspired reactive collision avoidance

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Abstract. Motivated by the design of a future autonomous, decentralized air traffic management system for runway-independent aircraft, a biologically-inspired reactive collision avoidance algorithm is developed for a simple model of managing multiple vehicle systems. Techniques using gyroscopic forces and scalar potentials result in all vehicles arriving at their destinations within a reasonable time, with no collisions. Demonstrations involving over 100 vehicles in a crowded cross-traffic setting with buildings have been simulate with no collisions observed. The control approach has two key features, both of which are desirable for on-board implementation: it uses only locally sensed information and is computationally cheap.

1. Introduction

Runway-independent aircraft (RIA), such as vertical takeoff and landing vehicles, have been proposed to increase passenger throughput by removing medium haul ($<$ 400 nautical miles) traffic from congested runways at commercial airports [6]. The proliferation of RIA could lead to complex cross-traffic patterns, especially in previously under-utilized urban areas. Centralized air traffic management, in which trajectory planning and collision avoidance for all vehicles is performed simultaneously, could increase air traffic controller workload leading to conflict-related delays and even further congestion.

Consequently, a decentralized approach may be favored in which trajectory planning and collision avoidance is implemented on-board each vehicle in real-time. In this paper, we consider a simple model of a 3-dimensional crowded airspace sector consisting of acceleration-limited vehicles in a high-rise urban environment. We implement steering and speed control laws in order to move a large number of vehicles from their starting points to designated target points within a reasonable amount of time and with no collisions. We demonstrate vehicles, subject to acceleration limits, that steer a collision-free path, threading through the "crowd" of other vehicles and obstacles while attempting to take the most direct path to their destinations. Reactive collision avoidance is used, where a collision avoidance maneuver is performed only when a possible collision is detected.

The decentralized control behavior we seek is inspired by that observed in biological systems of self-propelled agents exhibiting reactive collisional avoidance, such as pedestrian traffic and flocks of birds [3]. Natural multi-body biological transportation systems are autonomous, decentralized, safe and efficient, avoiding collision even in crowded conditions.

This work builds upon that of Justh et al. [4] and Chang et al. [2], who consider reactive collision avoidance for multiple agent systems, creating flocking behavior, but not using the "boids" methodology of [5]. Instead, techniques using gyroscopic forces and scalar potentials are used, resulting in collision avoidance between the agents as well as with obstacles.

2. Control Law

Suppose we have a group of fully actuated vehicles obeying a second-order translational dynamics. Since each vehicle will implement the same control law (modulo the destination point), we only need develop the control law for one vehicle.

For the purposes of discussion, we assume that each vehicle is a point of unit mass. Let us also suppose that fixed obstacles are cylindrical "buildings" attached to the ground, the xy-plane.

We desire a feedback control law to (asymptotically) drive vehicle i to a target point $\mathbf{q}_T \in \mathbb{R}^3$ without colliding with other vehicles or fixed obstacles. A *detection shell*, a ball of radius $r_{\rm det}$, is given to the vehicle such that the vehicle can respond to any obstacle within this shell, be it a neighboring vehicle or a building. For the purpose of designing the control law, let us refer to an obstacle of vehicle i as a neighboring vehicle within vehicle i's detection shell. Each point particle vehicle is surrounded by a spherical *safety shell* of radius $r_{\rm saf}$ which encloses the (perhaps non-convex) physical shape of the vehicle. A collision is considered to occur if a vehicle's safety shell intersects the safety shell of another vehicle or an obstacle's safety shell, which for a building are composed of cylinders or spheres of radius $r_{\rm obs}$.

The dynamics of the vehicle are given simply by

$$\ddot{\mathbf{q}} = u, \tag{1}$$

where $\mathbf{q} \in \mathbb{R}^3$. The control law u consists of three parts as follows:

$$u = F_p + F_d + F_g \tag{2}$$

where F_p is the potential force driving the vehicle to the target point $\mathbf{q}_T$; F_d is a damping force, including a *braking* force; F_g is a gyroscopic or *steering* force. The three forces are of the following form:

$$F_p = -\nabla V(\mathbf{q}), \qquad F_d = -D(\mathbf{n}, \dot{\mathbf{q}})\dot{\mathbf{q}}, \qquad F_g = S(\mathbf{n}, \dot{\mathbf{q}})\dot{\mathbf{q}}, \tag{3}$$

where $\mathbf{n}$ denotes the vector from the vehicle to its nearest obstacle (in particular, the nearest point on the nearest obstacle), V is a potential function on $\mathbb{R}^3$, the matrix D is symmetric and positive-definite, and the matrix S is skew-symmetric, i.e., $S^T = -S$.

One suitable choice for the potential function is a simple quadratic in the distance to the target $V(\mathbf{q}) = \frac{1}{2}r_T^2 = \frac{1}{2}||\mathbf{q} - \mathbf{q}_T||^2$. The matrix S is chosen to be an infinitesimal rotation about the vector $\mathbf{n} \times \dot{\mathbf{q}}$ when $\mathbf{n} \times \dot{\mathbf{q}} \neq 0$. When $\mathbf{n} \times \dot{\mathbf{q}} = 0$, a preferred rotational direction be chosen. The matrix $D(\mathbf{n}, \dot{\mathbf{q}})$ in the damping term can be thought of as an imposed braking term that varies with the relative distance between the vehicle and its nearest obstacle as well as the vehicle's speed.

If more than one obstacle is within the vehicle's detection shell, *the vehicle only reacts to the one which poses the greatest collision threat*. This is the obstacle with which the vehicle has estimated the shortest time to collision. If there is no obstacle within the vehicle's detection shell, the gyroscopic and braking forces are zero. In addition, each vehicle does not react to obstacles "behind" them, even if the obstacle is within the detection shell.

The magnitude of the gyroscopic and braking forces varies as a negative exponential of the distance between the vehicle and its nearest obstacle, for example:

$$D(\mathbf{n}, \dot{\mathbf{q}}) = (D_1 \exp(-||\mathbf{n}||) - D_2)/\|\dot{\mathbf{q}}\|, \tag{4}$$

where D_1 and D_2 are positive constants chosen such that the braking acceleration is bounded by some specified maximum $D_{\rm max}$ and is zero when the obstacle is on the edge of the detection shell. Similarly for the gyroscopic term, we can choose constants such that $\|F_g\| \leq S_{\rm max}$. An acceleration limit $\|u\| \leq u_{\rm max}$, where $r_{T,\rm max} = u_{\rm max} - (D_{\rm max} + S_{\rm max}) \geq 0$, requires that the distance to the target be constrained by $r_T \leq r_{T,\rm max}$.

3. Numerical Demonstration

We apply the control law developed in the previous section to a group of 64 vehicles moving from starting to final destinations (fixed sites). For example, in the upper left-hand panel of Figure 1 we consider four clusters of color-coded vehicles which are on four sides of a group of buildings. The sites are occupied by one vehicle each at

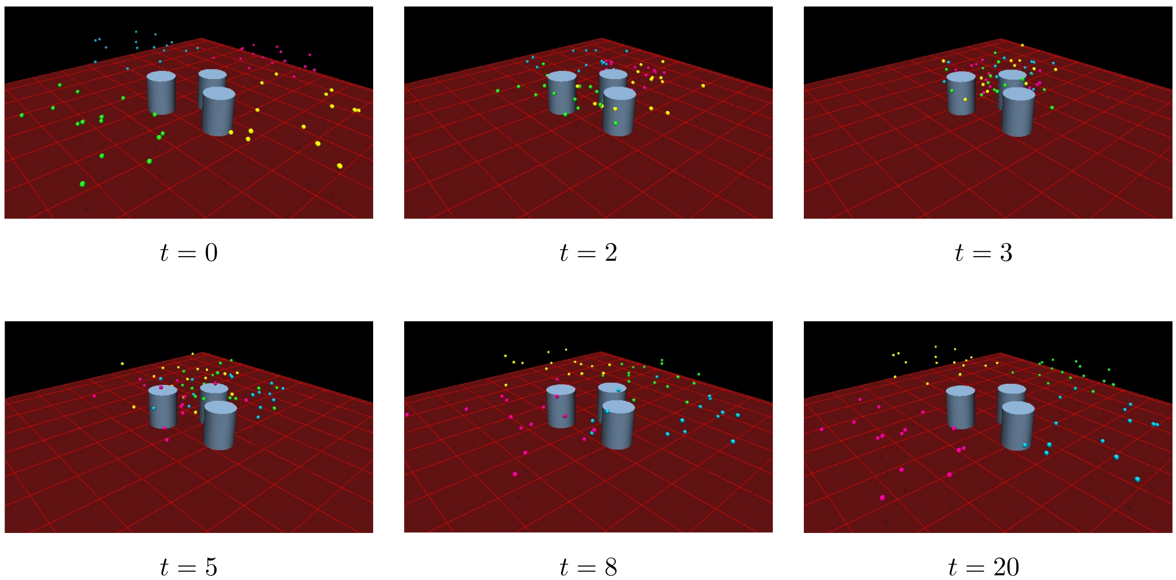

Figure 1. Snapshots of collision avoidance paths for 64 vehicles.

$t = 0$, where the vehicles' safety shells are shown. All vehicles are randomly assigned a unique destination site in the cluster on the opposite side of the buildings. Starting the vehicles from rest, we implement the steering and braking control laws (3) to drive all vehicles to their destination site autonomously. Snapshots of the simulation are shown in Figure 1. The full animation from several viewpoints can be found at `http://www.cds.caltech.edu/~shane/movies/index.html#avoidance`.

The clusters were chosen such that the vehicles converge upon the area surrounding the buildings at approximately the same time, leading to a very crowded intersection. Despite the high density of vehicles, there are no collisions, and each of the 64 vehicles gets to its intended destination. We have performed the same procedure for 128 vehicles (4 clusters of 32) and also observed no collisions.

4. Conclusions and Future Work

We have presented an approach for real-time, autonomous, decentralized air traffic control appropriate for a simplified model of multiple acceleration-limited vehicles in a crowded cross-traffic environment amongst buildings. A biologically-inspired control law for each vehicle was presented, consisting of (i) a simple potential function to guide the vehicle to its target, augmented by (ii) reactive collision avoidance of obstacles and other vehicles using gyroscopic and braking forces. The control law has two key features, both of which are desirable for on-board implementation: it uses only locally sensed information, the relative position of nearby vehicles, and is computationally cheap. It was demonstrated numerically that for large numbers of vehicles (about 100), all vehicles can arrive at their destinations with no collisions.

In this formalism the possibility exists of turning a passenger safety guarantee into a mathematical proof of non-collision (in the spirit of [1]). Moreover, it may be possible to derive an upper limit on the number of vehicles that can safely operate in a given airspace with a control law of the form given here.

In the future, one interesting direction is to first investigate the application of these control laws within the context of a testbed of unmanned micro air vehicles, incorporating realistic aerodynamics into the model based on experimental data from the aircraft. Experimentation will also allow us to identify the minimum on-board control, navigation, and sensing technology level required for all aircraft participating in such a system. We will also consider collision avoidance trajectories optimized in real-time with respect to fuel, time, and passenger comfort. One can also consider avoidance of other "obstacles" to be treated as impenetrable barriers, such as commercial fixed-wing aircraft corridors, regions of inclement weather, or specified no-fly zones.

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