Generation of Conflict Resolution Maneuvers for Air Traffic Management*

Jana Košecká, Claire Tomlin, George Pappas, and Shankar Sastry
Department of Electrical Engineering and Computer Sciences
University of California at Berkeley
Berkeley, CA 94720

Abstract

We explore the use of distributed on-line motion planning algorithms for multiple mobile agents, in Air Traffic Management Systems (ATMS). The work is motivated by current trends in ATMS to move towards decentralized air traffic management, in which the aircraft operate in "free flight" mode instead of following prespecified "sky freeways". Conflict resolution strategies are an integral part of the free flight setting. The purpose of this paper is to obtain a set of maneuvers to cover all possible conflict scenarios involving multiple agents. A distributed motion planning algorithm based on potential and vortex fields is used. While the algorithm is not always guaranteed to generate flyable trajectories, the obtained trajectories can serve as qualitative prototypes for coordination maneuvers between multiple aircraft. The actual maneuvers are generated by approximating these prototypes with trajectories made up of straight lines and are further verified using hybrid verification techniques.

1 Introduction and Motivation

The need for new advances in Air Traffic Management Systems (ATMS) arises due to the steady growth of air traffic at urban airports and the increasing demands for efficient control, scheduling and landing of larger numbers of aircraft. Recent technological advances, such as on-board computing facilities and Global Positioning Systems (GPS) make the use of modern automated control techniques feasible. In addition, there is a need to simplify and reduce the workload of human air traffic controllers who play the key role in the current centralized system. The individual aircraft have very little autonomy and must travel along prespecified "sky freeways" and have preset landing approach patterns. The main task of air traffic controllers is to maintain a minimum separation between aircraft; fuel consumption and travel times are not prime considerations of the controllers. Recent trends in air traffic control suggest the concept of "free flight" as a step towards a more efficient utilization of the airspace and the objectives of individual aircraft. Free flight distributes some of the control authority to the aircraft, thereby reducing the workload of air traffic controllers and making the system more reliable and less prone to the failures of the central controller. The conflict resolution strategies are at the top of the agenda for making free flight a reality. We consider the conflict resolution problem as a part of the overall ATMS architecture. In Section 2 we overview the proposed architecture [SMT+95] and describe the existing approach to conflict resolution. In Section 3, we discuss the multiple robot motion planning problem, and in Section 4, we demonstrate a distributed algorithm for a more generalized set of collision avoidance maneuvers. Section 5 discusses briefly the approximation and verification of the coordination maneuvers.

2 Air Traffic Management and Conflict Resolution

In the proposed ATMS architecture of [SMT+95], each aircraft follows a nominal path from source airport to destination airport described by a sequence of *waypoints*, which are fixed points in the airspace. This nominal path is calculated off-line in consultation with Air Traffic Control (ATC) and is designed to be optimal in some sense and conflict-free. However, bad weather, high winds, or schedule delays which cause conflicts with other aircraft may force the aircraft to deviate from this nominal route. In the current system, these deviations are calculated by the central ATC and each aircraft must obtain a clearance from ATC before altering its course. In the proposed ATMS, the aircraft may plan its own deviation trajectories without consulting ATC. This semi-autonomy is enabled by on-board conflict resolution algorithms.

Conflict resolution is addressed in the proposed architecture at two different ways [TPS96]. The first way to resolve the conflict is to perform *noncoopera-*

*This research has been funded by the ARO under MURI program DAAH04-96-1-0341, and by NASA under grant NAG 2-1039.

Proc. IROS 97 0-7803-4119-8/97/$10©1997 IEEE

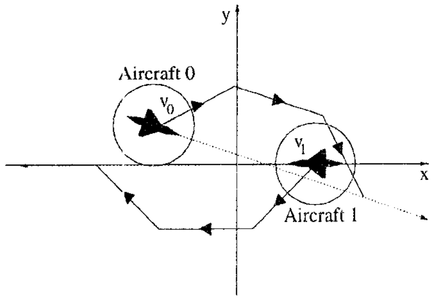

Figure 1: Generalized *head-on* conflict.

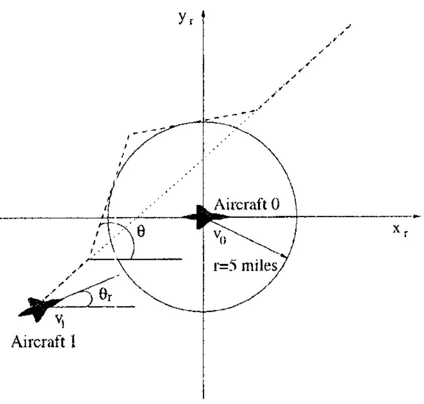

Figure 2: Generalized *overtake* conflict.

tive conflict resolution with no coordination between the agents. The agents are treated as players in an n-player, zero-sum noncooperative dynamic game. Each aircraft solves the game considering the worst possible actions of the other aircraft. In *cooperative conflict resolution* the aircraft perform coordinated predefined maneuvers in order to resolve the conflict. The class of maneuvers constructed to resolve conflicts must be rich enough to cover most possible conflict scenarios. Several qualitatively different conflict scenarios have been distinguished in [TPS96] and provably correct collision avoidance strategies proposed. Examples of *head-on* and *overtake* maneuvers can be seen in Figure 1 and 2.

In order to construct a complete set of collision avoidance maneuvers which cover general conflict scenarios involving more than two agents, there is a need to classify all kinds of possible collisions, and the maneuvers to resolve these. To do this, we use the strategy outlined in Figure 3. First we employ the automated method of potential field based motion planning to generate "prototype maneuvers", which inspire the actual collision avoidance maneuver. We believe that distributed on-line motion planning techniques and their application to ATMS can be inspirational for deriving a set of possible maneuvers for collision avoidance between aircraft. In spite of the fact that

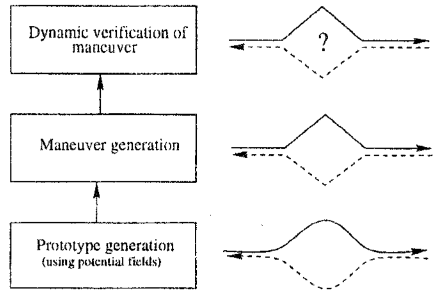

Figure 3: Generation of Potential Field inspired maneuvers.

the feasibility of the individual trajectories can be asserted by simulations, the proof of the safety of the maneuvers for dynamic models of aircraft remains a challenging problem. It is for this reason that we wish to construct the simplest possible maneuvers from the prototypes, those made up of straight lines. This discretized version of the maneuvers can be modeled as a hybrid system can be proven to be safe using hybrid verification techniques. The verification step is crucial for building an off-line database of safe conflict resolution maneuvers, which could serve as an advisory to the air traffic controller.

3 Robot Collision Avoidance

There is a large number of theoretical studies in the classical motion planning literature regarding the multiple robot planning problem. Algorithms embedded in time-extended configuration space [ELP87] prove to be computationally hard, and with additional velocity bounds the multi-agent motion planning problem has been shown to be NP-complete [CR87]. In applications the scenarios considered most often involve navigation in the presence of other moving agents and obstacles [Mat95]. The proposed solutions are geared towards distributed settings, in which only the local information about the state of the environment and the other agents in the vicinity is available to each agent. These techniques are based on potential and vortex field methods [MO91] and the complexity is proportional to the number of agents. An attempt to guarantee that the agents achieve their goals without colliding with each other has been proposed by Masoud [Mas96]. In spite of the fact that collision avoidance is an integral part of agents' navigation capabilities, the requirements for safety and optimality have not been addressed to any great extent. This is partly due to the fact that the agent velocities have traditionally been relatively small and safety issues not so prominent: low velocity collisions occasionally occur, but various recovery strategies allow the agents to further pursue their tasks. In path planning for more than two agents, prioritized schemes have been used to fix the order in which the conflicts are resolved.

In our air traffic collision avoidance problem, we use the approach based on potential and vortex fields, yet we back away from attempting to prove that the resulting motions will always result in no collisions. We concentrate instead on describing the *qualitative* properties of the resulting motions, and then classifying them into discrete sets of avoidance maneuvers. These sets of maneuvers will then be proven to be safe using dynamic aircraft models.

4 Maneuver Generation

We adopt the potential and vortex field approach for distributed motion planning proposed in [Mas96]. In air traffic control the absence of stationary obstacles and the approximation of individual agents by circles with a specified radius constitute reasonable assumptions prior to formulating the collision avoidance strategy[1]. We consider the *planar* collision avoidance problem with multiple moving agents.

The planner is obtained by the superposition of several vector fields representing qualitatively different steering actions of each agent. Suppose we have m agents, with the ith agent represented by a circle with radius r_i and its configuration denoted by $\boldsymbol{x}_i = (x_i, y_i)$. The desired destination of the ith agent $\boldsymbol{x}_{di} = (x_{di}, y_{di})$ is represented by an attractive potential function:

$$U_a(\boldsymbol{x}_i, \boldsymbol{x}_{di}) = \frac{1}{2}(\boldsymbol{x}_{di} - \boldsymbol{x}_i)^2$$

In order to achieve the desired destination a force proportional to the negative gradient of the U_a needs to be exerted:

$$F_a(\boldsymbol{x}_i, \boldsymbol{x}_{di}) = -\nabla U_a(\boldsymbol{x}_i, \boldsymbol{x}_{di}) = -(\boldsymbol{x}_i - \boldsymbol{x}_{di})$$

To prevent collisions between agents i and j, the following spherically symmetric repulsive field $U_r(\boldsymbol{x}_i, \boldsymbol{x}_j)$ is associated with each agent:

$$U_r(\boldsymbol{x}_i, \boldsymbol{x}_j) = \begin{cases} -\frac{(\boldsymbol{r}_{ij} - (\boldsymbol{r}_j + \delta_{rj}))^2}{2\delta_{rj}} & \text{if } \boldsymbol{r}_j \leq \boldsymbol{r}_{ij} \leq \boldsymbol{r}_j + \delta_{rj} \\ 0 & \text{otherwise} \end{cases}$$

where $\boldsymbol{r}_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$ is the distance between the ith and jth agent, $\boldsymbol{r}_j$ is the radius of jth agent and δ_{rj} is the influence zone of its repulsive field. The repulsive force associated with this field is:

$$F_r(\boldsymbol{x}_i, \boldsymbol{x}_j) = \nabla U_r(\boldsymbol{x}_i, \boldsymbol{x}_j)$$

A vortex field, used to ensure that all agents turn in the same direction when encountering a conflict, is constructed around each agent tangential to the repulsive field $U_r(\boldsymbol{x}_i, \boldsymbol{x}_j)$:

$$F_v(\boldsymbol{x}_i, \boldsymbol{x}_j) = \pm \begin{bmatrix} \frac{\partial U_r(\boldsymbol{x}_i, \boldsymbol{x}_j)}{\partial y} \\ -\frac{\partial U_r(\boldsymbol{x}_i, \boldsymbol{x}_j)}{\partial x} \end{bmatrix}$$

Note that by the choice of the sign in the above vortex field expression one can determine the direction of the circulating field. Setting the direction to a particular sign for all agents corresponds essentially to a "rule of the road" which specifies the direction of the avoidance for conflict maneuvers. It is well known fact from the differential topology that a smooth vortex field on a sphere must have at least one singularity, which makes the extension of the vortex field technique to 3-D not straightforward.

The dynamic planner for a single agent in the presence of multiple agents is obtained by superposition of participating potential and vector fields and becomes:

$$\dot{\boldsymbol{x}}_i = \frac{F_a(\boldsymbol{x}_i, \boldsymbol{x}_{di})}{\|F_a(\boldsymbol{x}_i, \boldsymbol{x}_{di})\|} + \sum_j (k_{ri} F_r(\boldsymbol{x}_i, \boldsymbol{x}_j) + k_{vi} F_v(\boldsymbol{x}_i, \boldsymbol{x}_j))$$

where $j = 1, ..., m,\ i \neq j$. The contributions from repulsive and vortex fields range between [0, 1], increasing as the agent approaches the boundary of another agent. Normalization of the attractive field component makes its contribution comparable to the magnitudes of the repulsive and vortex fields. The strength of the field then becomes independent of the distance to the goal, capturing merely the heading to the goal. The individual contributions are then weighted by the by k_{ri}, k_{vi} and the resulting vector is again normalized and scaled by k_{di}, a constant proportional to the desired velocity of the ith agent. The velocity of ith agent is then:

$$\boldsymbol{v}_i = k_{di} \frac{\dot{\boldsymbol{x}}_i}{\|\dot{\boldsymbol{x}}_i\|}$$

In the following paragraph we demonstrate the capability of the planner to generate trajectories for general class of collision avoidance maneuvers.

Overtake conflicts: The *overtake* conflict can be resolved by the planner in several qualitatively different ways obtained by adjusting the parameters in the individual contributions of the participating vector fields. In the outlined experiments two agents having different velocities participate in conflict resolution. In Figure 4 agent 1 is 1.5 times faster than agent 0. In the top maneuver, agent 1 overtakes agent 0 and agent 0 moves away from agent 1, resulting in smaller deviations from the original trajectory for both agents. The strength of contribution from the repulsive and vortex fields is the same for both agents. Willingness of the slower agent to cooperate in the overtake maneuver can be modeled by the strength of the agent's

[1] For the purpose of air traffic control the aircraft is considered to be a "hockey puck" of a specified safety radius representing the desired clearance from the other aircraft.

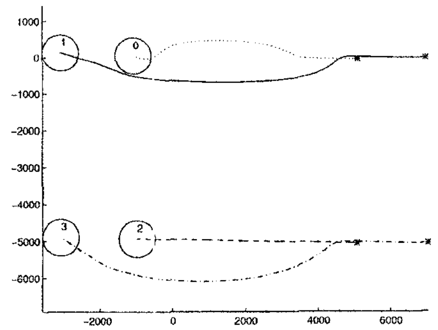

Figure 4: *Overtake* maneuvers. Top: $1.5k_{d0} = k_{d1}$, $k_{r0} = k_{r1} = k_{v0} = k_{v1} = 1.0$. Bottom: $1.5k_{d2} = k_{d3}$, $k_{r2} = k_{v2} = 0.0; k_{r3} = k_{v3} = 1.0$

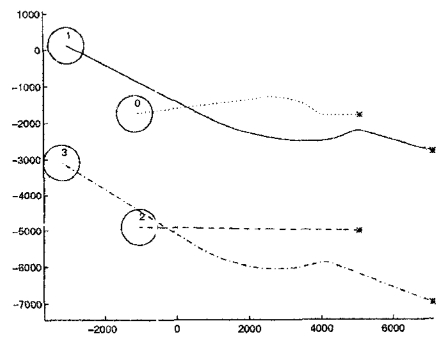

Figure 5: Generalized *overtake* maneuver. In the conflict at the top both agents participate in the maneuver while at the bottom the conflict is resolved solely by agent 3.

repulsive and vortex fields: in the bottom maneuver of Figure 4 the contributions of agent 2's vortex and repulsive fields are set to zero and agent 2 does not deviate from its original trajectory. Figure 5 demonstrates generalized overtake maneuvers where the agents are not initially aligned.

Head-on conflicts: Similarly, several qualitatively different *head-on* maneuvers can be generated by changing the contributions of individual fields. In Figure 6 there are two head-on maneuvers where both agents actively cooperate on resolving the conflict, i.e. the strength of the repulsive and vortex fields is the same for each agent. Figure 7 demonstrates generalized head-on maneuvers where the agents are not initially aligned.

Multiple aircraft conflicts: In the conflicts involving only two aircraft the number of possible conflict scenarios is quite low. When multiple aircraft are involved in conflict the vector field based planner is very instructional: the direction of the vortex field contribution serves as a coordination element between the

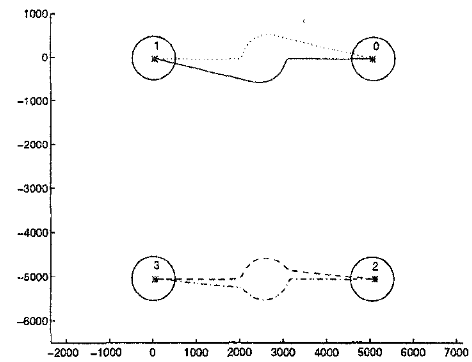

Figure 6: *Head-on* maneuvers. Top: symmetric head-on with all the parameters the same. Bottom: $k_{d2} = k_{d3} = 10.0$, $k_{r2} = k_{r3} = 0.3$, $k_{v2} = k_{v3} = 5.0$ with the influence of the vortex field emphasized.

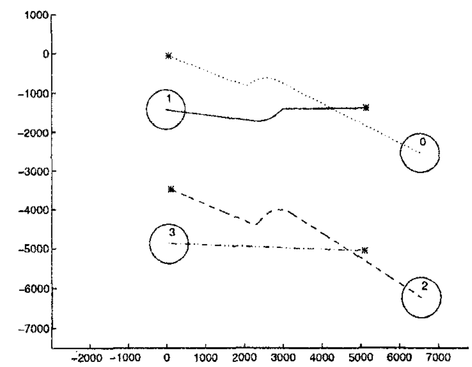

Figure 7: Generalized *head-on* maneuver. Top: the velocities of the agents are the same and both agents participate in the maneuver. Bottom: agent 3 does not participate in the maneuver since $k_{r3} = k_{v3} = 0$.

aircraft. Figure 8 depicts a symmetric *roundabout* maneuver similar to the one proposed in [TPS96]. The agents involved in the resolution of the conflict are homogeneous, having the same velocities, willing to participate equally in the maneuver (the strength of the repulsive and vortex fields is the same for all agents). Figure 9 demonstrates a scenario where agent 0 does not participate in the coordination (k_{v0} and k_{r0} are 0) and is willing only to adjust its velocity slightly. This particular conflict can be still resolved and the resulting trajectories are flyable.

Observations: The presented planner has the capability of changing the spatial behavior of individual agents and always resolved the conflict if the agents were homogeneous and there were no restrictions on the temporal profiles of the agents' paths. Given particular constraints on agents' velocities certain conflicts may result in "loss of separation" or trajectories which are not flyable, due to the violation of the limits on turn angles (Figure 10). In such cases the shape

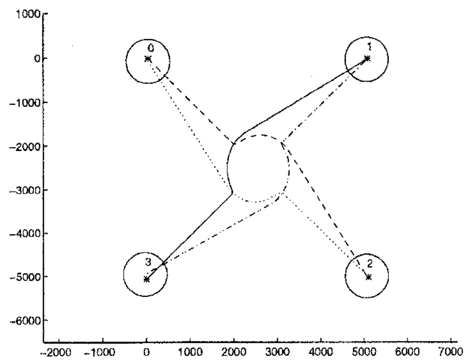

Figure 8: Symmetric *roundabout*, gain factors for individual agents are the same.

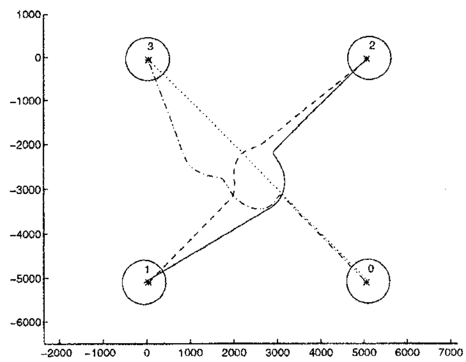

Figure 9: Partial *roundabout*, $k_{vi} = k_{ri} = 1.0$ and $k_{d0} = 0.5k_{di}$ for i = 1,2,3 with the maximal velocity of agent 0 reduced by a factor of 2 and $k_{r0} = k_{v0} = 0$.

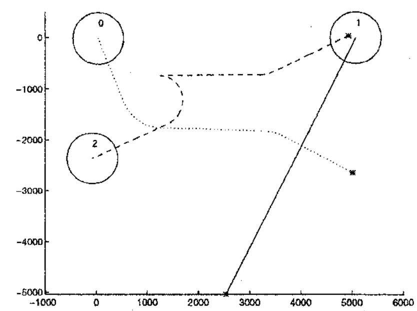

Figure 10: General conflict scenario. Trajectory of agent 2 is not flyable.

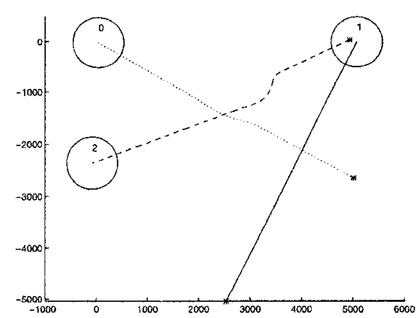

Figure 11: Velocity profile agent 2 is adjusted resulting in a flyable trajectory.

of the path can be affected by changing parameters of contributing vector fields. The adjustment of influence zones δ_{ri} and δ_{vi} as well as relative strength of the repulsive and vortex vector fields, k_{ri} and k_{vi}, can affect the turn angle and maximal deviation from the original trajectory needed to resolve the conflict. The change of the temporal profiles of the path by adjusting the velocities of individual agents (k_{di}) has the most profound affect on the capability of resolving general conflict scenarios. In Figure 11 the unflyable trajectory from Figure 10 can be changed by adjusting the velocity of agent 2 resulting in flyable trajectory.

5 Maneuver Approximation and Verification

The discretization of the prototype maneuver is motivated by techniques currently performed by air traffic controllers which resolve conflicts by "vectoring" the aircraft in the airspace. This is partly due to the current status of the communication technology between the air traffic control center and the aircraft as well as the state of current avionics (autopilot) on board of the aircraft which operates in a set-point mode. We consider two types of approximations: turning point approximation and offset approximation. The individual approximation can be obtained from the trajectories generated by the dynamic planner by recursive least squares linear fit (see Figure 12).

The approximation phase is followed by the verification of the obtained maneuvers. The purpose of the verification step is to prove the safety of the maneuver by taking into account the velocity bounds and sets of initial conditions of individual aircraft. The collision avoidance problem lends itself to a hybrid system description: the continuous modes of the hybrid model correspond to individual parts of the maneuver (e.g. straight, turn right θ_1 degrees, turn left θ_2 degrees) and the transitions between modes correspond to switching between individual modes of the maneuver. Within each mode the speed of each aircraft can be specified in terms of lower and upper bounds. This suitable simplification of the problem allows us to model the collision avoidance maneuver in terms of hybrid automata [ACHH93]. The verification results can assert that the maneuver is safe for given velocity bounds and given set of initial conditions. More details may be found in [KTPS97].

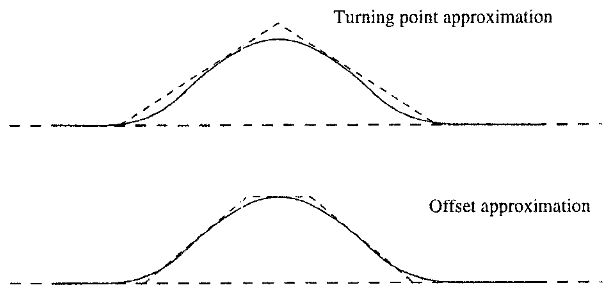

Figure 12: Turning point and offset approximation.

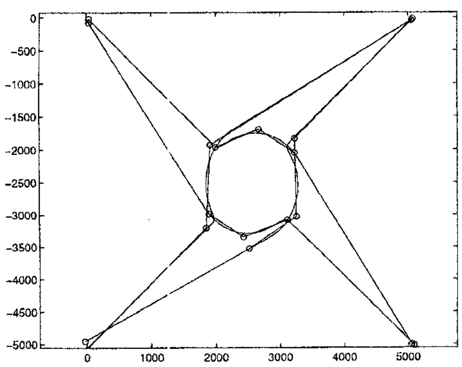

Figure 13: Discretized *roundabout* maneuver.

6 Conclusions

The previously presented simulation results suggest that the generalized *overtake* and generalized *head-on* maneuvers may be used to solve all possible two-aircraft conflicts. This conclusion is encouraging, since it allows us to classify two-aircraft maneuvers by the angle at which the aircraft approach each other (as in Figure 1), and to design simple deviation maneuvers as sequences of straight line segments which approximate the trajectories derived from the potential and vortex field algorithm.

For more than two aircraft the obtained discretized version of the *roundabout* maneuver (see Figure 13) is similar to the one suggested in [TPS96]. For this maneuver the radius of a circular path around the conflict point is proportional to the influence zones of the aircrafts' repulsive and vortex fields.

We propose this methodology as a suitable step of automation of conflict resolution in ATMS given currently available technology. However the proper classification of all conflict scenarios and maneuvers remains a challenging problem.

References

[ACHH93] R. Alur, C. Courcoubetis, T. A. Henzinger, and Pei-Hsin Ho. *Hybrid Systems*, chapter Hybrid automata: An algorithmic approach to the specification and verification of hybrid systems, pages 366 – 392. Springer Verlag, 1993.

[CR87] J. Canny and J. Reif. New lower bound techniques for robot motion planning problems. In *Proceedings of the 28th Annual IEEE Symposium on Foundations of Computer Science*, pages 49–60, 1987.

[ELP87] M. Erdman and T. Lozano-Perez. On multiple moving objects. *Algorithmica*, 2:477–595, 1987.

[KTPS97] J. Košecká, C. Tomlin, G. Pappas, and S. Sastry. Verification of cooperative conflict resolution maneuvers. In *Submitted to Hybrid Systems V*, 1997.

[Mas96] A. Masoud. Using hybrid vector-harmonic potential fields for multi-robot, multi-target navigation in stationary environment. In *Proceedings of the IEEE Conference on Robotics and Automation*, pages 3564–3571, 1996.

[Mat95] M. J. Mataric. Issues and approaches in the design of collective autonomous agents. *Robotics and Autonomous Systems*, 16(2-3):321–331, December 1995.

[MO91] C. De Medio and G. Oriolo. Robot obstacle avoidance using vortex fields. In S. Stifter and J.Lenarcic, editors, *Advances in Robot Kinematics*, pages 227 – 235, 1991.

[SMT+95] S. Sastry, G. Meyer, C. Tomlin, J. Lygeros, D. Godbole, and G. Pappas. Hybrid control in air traffic management systems. In *Proceedings of the IEEE Conference in Decision and Control*, pages 1478–1483, 1995.

[TPS96] C. Tomlin, G. Pappas, and S. Sastry. Conflict resolution for air traffic management: A case study in multi-agent hybrid systems. Technical report, University of California at Berkeley, 1996.