

Technical Correspondence

Reliably Creating Collision Avoidance Advisories in Piloted Simulations

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Abstract—We demonstrate a novel method to reliably generate collision avoidance advisories, in piloted simulations, by the widely used traffic alert and collision avoidance system (TCAS). The TCAS advisory issued to a pilot is highly sensitive to the trajectory of an intruder aircraft relative to the ownship flown by the pilot. In realistic piloted simulations, a prescribed intruder trajectory will not reliably result in the relative dynamics that lead to a desired TCAS advisory. Further, the complexity of the TCAS logic requires a novel method for mapping trajectories to the range of possible advisories. We propose to use a rapidly exploring random tree algorithm in large-scale fast-time simulations to establish the mapping between the space of relative trajectories and TCAS advisories. These trajectories are then created in piloted simulations through guidance algorithms. Results demonstrate the ease of use and robustness of this method, and its potential for pilot training and for research and development.

Index Terms—Air traffic control, collision avoidance, human factors, simulation.

I. INTRODUCTION

A fundamental metric of safety in air traffic is the minimum separation distance between aircraft. Maintaining safe aircraft separation is ultimately the responsibility of the pilot, supported by the air traffic control (ATC) and onboard equipment. The traffic alert and collision avoidance system (TCAS¹) is such a system which issues last-resort collision resolutions advisories (RAs). RAs indicate an avoidance maneuver to the pilot, which, if followed, will resolve the situation.

Research, development, and pilot training on the TCAS and similar collision avoidance systems depends on flight simulators, which have been historically limited by their ability to create desired collision avoidance trajectories. Getting TCAS advisories to occur in a controlled fashion within human subject flight simulation experiments requires either undesirable or unrealistic limitations placed on the participant

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¹TCAS is a particular commercial implementation of an airborne collision avoidance system (ACAS). The method presented in this paper can extend to any desired ACAS.

pilots, unrealistic conflict-seeking behavior by the scripted aircraft, and/or luck.

The purpose of this paper is to establish a method that enables favorable and repeatable test conditions for human-in-the-loop (HITL) experiments involving the TCAS. To be realistic, HITL simulators must allow pilots to control their own trajectory within the limits of air traffic instructions (e.g., choose their own climb/descent rate to a specified altitude, choose when to extend flaps and gear, etc.). However, because of the complexity of the TCAS logic and the dimensionality of the trajectory space, the type of TCAS advisory issued to a pilot is highly sensitive to the trajectory of an intruder aircraft relative to the ownship. Therefore, using prescribed intruder trajectories will not reliably result in the relative dynamics that lead to desired TCAS advisories.

Thus, a novel method is needed to identify the mapping between TCAS resolutions advisories and aircraft trajectories. We use a randomized algorithm called a rapidly exploring random tree (RRT) to explore the space of intruder trajectories. The TCAS logic evaluates the different intruder trajectories relative to the ownship and issues the relevant RA (if any).

Fundamental to this study is the ability to guide the intruder. The trajectory definition and guidance used in the simulator are presented in Section III. For the purpose of generalizability, the intruder trajectories are defined in a frame of reference relative to the ownship. This definition, together with an adaptive guidance system, enables a robust implementation of traffic scenarios when the pilot flies a reasonably different ownship trajectory than expected. Section IV elaborates on the RRT method used to search trajectories creating the desired TCAS advisories. The robustness and time efficacy of the method in a simulator study is discussed in Section V.

II. BACKGROUND

A. Traffic Alert and Collision Avoidance System

The TCAS has been required for many aircraft since 1993 [1]. TCAS is currently required on all commercial turbine-powered transport aircraft with more than 30 passenger seats, or maximum takeoff weight above 33,000 lbs; other aircraft have also been installing it voluntarily. The system displays the location and altitude of aircraft within a selected range and provides an alert based on time to conflict. The initial alert is a traffic advisory (TA), followed by an RA [2].

The RA determines an allowable range of vertical speeds which may require vertical maneuvering by the ownship aircraft, or may constrain the aircraft from increasing or decreasing vertical speed. Furthermore, if both aircraft are equipped with the TCAS, their maneuvers are coordinated to operate in opposing climb/descent senses.

B. Pilot Interaction

Federal Aviation Administration (FAA) regulations [3] provide specific guidelines for pilot interaction with the TCAS. This document reiterates that the TCAS is a backup safety system that depends on immediate and correct crew response. However, compliance with TCAS, i.e., cases when pilots followed the advised vertical maneuver, has been historically lower than expected [4].

In surveys and other studies, pilots have often described TCAS advisories as false or erroneous advisories [5]. However, comparing the pilot-reported rate of false or inappropriate advisories with the aggregate TCAS statistics suggests that the TCAS is in fact functioning according to its specifications, albeit not according to pilots' intuition

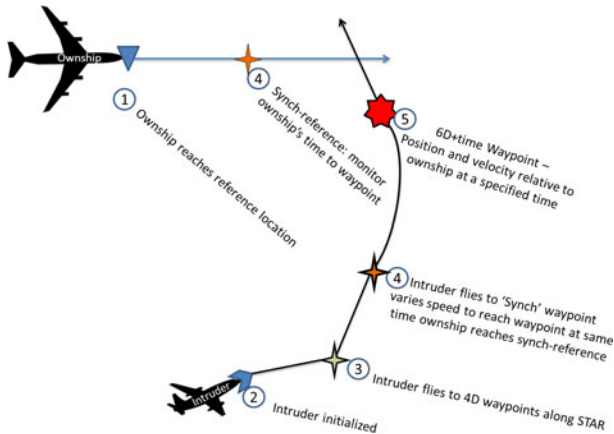


Fig. 1. Intruder trajectory relative to the ownship in a typical scenario.

[6]. Factors leading to inappropriate reactions during conflict situations may be a combination of visual acquisition of the intruder, poor pilot situational awareness of traffic, and poor pilot understanding of the TCAS [7], as FAA regulations allow pilots to disregard an RA if they have visual acquisition and deem the maneuver not necessary.

The ability to reliably create specific RAs in piloted simulations is an important factor supporting pilot training on the current TCAS and future development of other aircraft collision avoidance systems, more generally known as an airborne collision avoidance system (ACAS). However, this ability has not been achieved previously. For example, in a seminal experiment for the development of TCAS [8], which consisted of six two-man crews and 70 flights lasting 31 min each, the introduction of 970 intruder aircraft resulted in 465 TAs “because of unforeseen pilot action,” of which only 261 progressed to RA. No mention is made of the type of RA desired in each scenario.

Older studies [9] used an even more simplified logic with no dynamics to simulate the intruder trajectories. In a more recent experiment, 23 pilots flew two 35-min segments each [10]. While 276 combined TA/RA events were planned, 273 TAs and 251 RAs were effectively obtained. The 22 missed RAs were due to pilot maneuvering. Again, no mention is made of the type of RA desired in each scenario.

III. SIMULATED INTRUDER TRAJECTORY

This section presents the intruder guidance logic used in the simulation to steer the intruder along waypoints defined relative to the ownship.

A. Trajectory Waypoints

The intruder dynamics rely on differential models used previously in ATC simulations [11]. Trajectories are defined by 6-D waypoints: Three dimensions represent the spatial position of the waypoint, and three dimensions represent the velocity vector at that location. Given the objective of reliably obtaining RAs, these waypoints can be defined in the ownship reference frame. Thus, the mappings can be generalized to any ownship trajectory.

Fig. 1 shows the trajectory implementation. The intruder uses two kinds of waypoints in its trajectory. After initialization, the intruder flies along absolute 4-D waypoints (location + time) which follow a standard terminal arrival route. The resulting trajectory of the intruder is indistinguishable from those of surrounding traffic. When the ownship passes a synchronization waypoint, the intruder starts following relative 6-D waypoints (with time constraints to ensure convergence). The intruder, thus, adapts to the ownship’s trajectory in order to generate an RA.

B. Intruder Guidance

The guidance logic has two steps. First, a commanded trajectory is interpolated between the given waypoints. If only one waypoint is given, then the trajectory is a linear extrapolation with steady altitude, heading, and speed. If two or more waypoints are given, the interpolated trajectory is a piecewise parabolic between the two waypoints, such that additional degrees of freedom allow position and velocity constraints at the waypoints to be controlled.

The second step is the execution of the intruder trajectories. These trajectories serve as commands to the aircraft dynamic model, which is subject to limitations on aircraft performance. The resulting trajectory is, thus, realistic with respect to the aircraft performance specifications, which may not achieve the full parabola. The equations defining the aircraft guidance and dynamics are taken from [12].

IV. MAPPING TRAJECTORIES TO RESOLUTIONS

This section illustrates how an RRT can be used to map intruder trajectories to the TCAS advisories they create. The inverse mapping can then be used to identify the intruder trajectory most likely to create a desired RA.

A. Trajectory Space Dimensionality

Through the inverse mapping method, the trajectory space can essentially be partitioned into inverse images of the respective RAs. Even if the intruder trajectory is defined by only a single or pair of waypoints, the dimensionality of the problem makes a complete search intractable: 3×10^8 possibilities for a single waypoint (corresponding to 15–20 variations in each dimension of the waypoint) become 9×10^{16} permutations for two waypoints. These numbers are impractical in terms of the processing times required to fully map the space. Fortunately, the full-infinite trajectory space is of no interest for two reasons. First, only trajectories from a restricted subspace can lead to RAs. Second, corresponding to the model of intruder guidance given in Section III, we are only using the least number of waypoints sufficient to achieve desired RAs (two in this case).

Thus, the RRT algorithm [13] provides a more efficient method as a good compromise between an exhaustive space search and a pure random walk. Furthermore, building a tree structure to connect the random samples adds information and provides a more meaningful description, as relations of proximity and boundary become explicit. Most importantly, the method returns approximate results on the space partition from the early stages of computation, and these results can be further refined as desired through more computation.

B. Rapidly Exploring Random Tree Algorithm

RRT is an algorithm to explore and fill an open space by randomly constructing a tree. The tree is constructed in such a way that every new node defined in the search space is added to the tree by connecting it to the closest vertex. The more samples are generated, the finer the sampling and the shorter the tree edges. This heuristic goes a long way to accelerate the computational process by providing a rough initial estimate, which is then improved with additional iterations. The RRT algorithm is especially well suited to the mapping of complex (non-convex and high-dimensional) spaces. The conventional application of RRT is robotic path planning that involves obstacles and differential constraints [14]. However, the previous description of space exploration may also be understood abstractly. This has led us to use this method to map the trajectory space according to RA outcomes. For a precise description of the RRT algorithm in its original form, see [14]. The behavior of the algorithm as applied here is as follows.

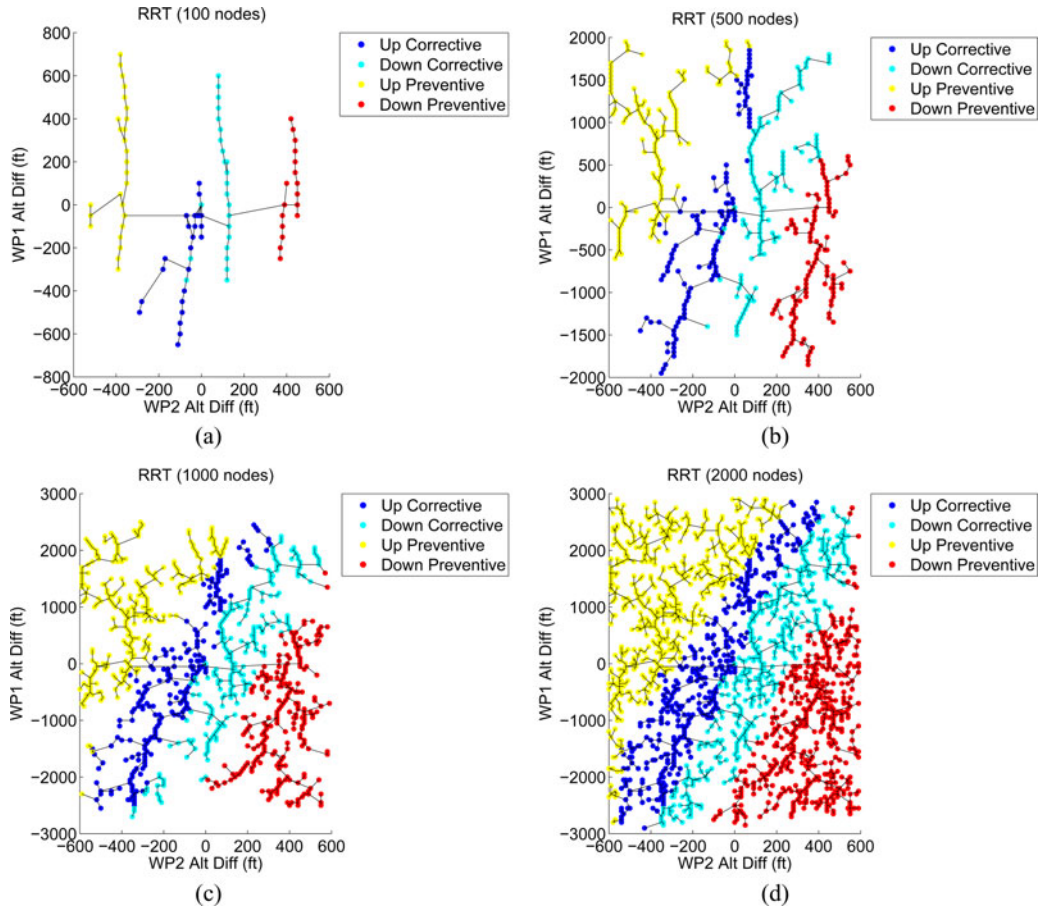


Fig. 2. Construction of the RRT in the trajectory waypoint space. (a) 100 nodes. (b) 500 nodes. (c) 1000 nodes. (d) 2000 nodes.

- 1) At every iteration, a 12-D sample is defined. The sample corresponds to a trajectory with two 6-D waypoints. The selection of the sample is biased toward the largest unexplored region of the search space.
- 2) The node in the tree that is closest to the new sample is identified. The distance used is the Euclidean norm (in normalized coordinates).
- 3) The sample is projected toward the closest node, so that its distance to the tree does not exceed a certain length. The distance is inversely related to the density of points in the tree. Nodes will be far apart and spread over the space when the search begins, and get closer together at every iteration.
- 4) The projected sample is linked to the tree with a new edge and becomes a new node. The TCAS algorithm evaluates the corresponding trajectory for a possible RA.
- 5) The newly created node is tagged with what RA, if any, is generated.
- 6) The tree is then ready for a new sample.
- 7) A search is deemed complete when the RRT space has been searched to an adequate level of granularity (the authors typically constrained some of the search variables and allowed the tree to grow to as much as 10 million nodes).
- 8) The nodes situated as close to the center of each RA region are selected as the intruder trajectories in the simulator. Well-centered nodes are the most likely to generate the desired RAs,

since small changes that can occur under the relative conditions between ownship and intruder still result in a node within the RA region. The boundaries of the RA regions are defined by the edges which connect two nodes labeled with two different RAs.

C. Trajectory Space

The RRT method maps the TCAS logic to the trajectories which result in each specific RA. As an example of the insight provided by this mapping, Fig. 2 shows a tree constructed by varying only two states in the 12-D trajectory space. The ownship conditions are set at 7000 ft altitude, level flight, 225 knots speed. The intruder starts with a head-on trajectory, level. Only two of the intruder states are varied in this example: relative altitudes at the first and the second waypoints. All other ten states would normally be varied, but are fixed in this example so that the mapping can be accurately portrayed in two dimensions. The growth of the tree reveals an obvious partition of the space in terms of corresponding RAs.

The mapping between the waypoint space shown here and the actual intruder trajectory in the simulation is neither transparent, nor is it bijective. But this mapping has the advantage of encapsulating both the TCAS logic and the intruder guidance logic, and thus, provides a true black box approach with accessible controllability of the outcome in HITL simulations.

TABLE I
EXPERIMENT DESIGN AND RRT METHOD RELIABILITY

Scenario	RA Situation	RA Occurrence	RA Success
A	Climb	100%	100%
B	Climb, conflicting radio information	100%	57%
C1	Descend	100%	100%
D1	Descend	88%	88%
E	Crossing Descend	100%	88%
F	Crossing Descend	100%	94%
H	Descend	100%	69%
C2 - manual	Climb	100%	82%
D2 - manual	Monitor Vertical Speed	69%	63%
G - manual	TA only	n/a	n/a

V. EXPERIMENTAL APPLICATION

This section describes the fidelity achieved by the RRT method in a recent HITL simulation study with the TCAS.

A. Overview of Piloted Human-in-the-Loop Simulator Study

The HITL experiment examined pilot responses to the TCAS in the context of an integrated air traffic control and flight simulator facility [15]. The results of this study are outside the scope of this paper and are reported in [15]–[17]. The exact TCAS logic was used, as defined in the minimum operational performance standards (MOPS) for two-aircraft conflicts. The MOPS are official standards for the TCAS jointly defined by the Radio Technical Commission for Aeronautics and European Organization for Civil Aviation Equipment [18]. Accurate position information was used in the experiment, thus, disabling the filtering algorithms in the TCAS tracking logic. This purposeful choice by the authors was intended to reduce variability in the study that might have originated from noisy information. Therefore, pilot traffic perception, RA, and reaction to the alert could be accurately controlled.

The air traffic simulator replicated traffic around the Dallas-Fort Worth airport. Sixteen airline pilots flew a medium-fidelity simulated B747-400 under instrument meteorological conditions [19] while interacting with an experimenter acting as air traffic controller. The surrounding air traffic appeared to the pilot on the TCAS traffic situation display.

Typically, piloted flights began around an altitude of 10,000–20,000 feet and lasted 15 min. Each pilot performed eight flights, and in each flight pilots encountered two traffic scenarios. Some of scenarios resulted only in TAs and required no maneuvering, while other scenarios resulted in TAs followed by RAs. The RA types and locations for the different scenarios are shown in Table I. The intruder trajectories for scenarios C2, D2, and G were manually designed. All other scenarios used output from the RRT search method.

B. Scenario Creation

To avoid any bias, the manual scenarios were created by the lead experimenter, not by the lead developer of the RRT method described in this paper. As the project director for the flight simulator experiment, her/his intention for all scenarios was to establish useful test conditions. Used in a resource- and time-constrained flight simulator study, each scenario represents an important test condition applied to only a limited set of pilots from the subject pool.

Scenarios were first sketched out on paper to identify key variables predicted to influence the type of TCAS RA they would generate. These variables were then mapped to intruder trajectories that were scripted into the simulation. However, none of these first estimates of intruder trajectories were found to be sufficient and they were iterated through repeated runs of the flight simulator in real-time with experimenters playing the role of an actual pilot. This averaged roughly a day of

flight simulator flights per scenario for those that were configured manually, until an exact specification of intruder trajectory was found that appeared to be robust with respect to RA occurrence, albeit not always RA success, i.e., generating an RA but not always returning the desired RA type.

In contrast, the scenarios developed using RRT started with the same paper sketch to identify those initial segments of the intruder trajectory that would appear to be realistic, in terms of the intruder originating from actual traffic streams in a manner that would make sense to the pilot. The RRT method was then used to identify the relative trajectory for this traffic following its origination from a traffic stream. Once this trajectory was identified, it was entered in the simulator and a single simulator flight was generally performed to verify that its parameters had been entered without error, as proven by the exact RA type that was desired.

Therefore, in all studies involving pilot responses to the TCAS, including the manual scenarios C2 and D2, the best intent was made to create robust scenarios. The primary purpose of these scenarios was not to serve as a baseline for the RRT method, but to setup test conditions involving human subjects in an expensive and difficult simulator test [15].

Thus, an essential advantage of the RRT method is its ease of use. Relative to a manual parameterization, which is a laborious and unrepeatable process of trial and error, the RRT method was found to provide fast and generalizable output that specified the commanded intruder trajectory exactly. This method, here applied to generating RAs, can be used to establish traffic events in a general sense. Such means of testing are key to the development of the ACAS X [20] and other related systems which are in turn vital to the development of the Next Generation Air Transportation System.

C. Rapidly Exploring Random Tree Method Reliability

The main utility of the RRT method comes from its time efficacy, its repeatability, and lack of reliance on expertise compared with manual scenario design. Furthermore, the reliability of the RRT method is apparent from the ratios shown in Table I, in terms of RA occurrence (cases when an RA was triggered) and RA success (cases when the specific desired RA was triggered). The authors wish to stress that the actual TCAS logic as defined in the MOPS [18] was used. Therefore, all generated RAs meet required criteria, and are considered to be “true”. Furthermore, all the RAs generated here would likewise be generated in real operations with the same traffic conditions. The experimental setting presents what a pilot would face, and the purpose of the scenarios was to test pilot responses to the TCAS [15]. The authors do not seek to debate whether every TCAS RA “should” have been issued, but to generate test conditions that do in fact result in RAs according to the TCAS logic.

The RRT method was extremely effective in generating an RA, with 100% RA existence in all but one scenario where it was used. Scenario D1 is the exception, having an 88% RA occurrence rate, although when an RA did occur, it was of the expected type. Crossing descents such as those used in traffic scenarios E and F are the RAs most sensitive to variation in the ownship trajectory, and are only possible within a small range of relative altitudes and altitude rates. The precision requirements, thus, explain the imperfect generation of crossing RAs in a HITL simulation, indicated by the lesser RA success ratios. Furthermore, scenario B involved contradictory information communicated to the pilot over the radio, which further exacerbated variability in the trajectory flown by the pilot. Scenarios C2 and D2 were scripted “manually,” to represent conflicts in particular traffic instances such as during parallel landing approach, and do not use output from RRT.

Scenario G did not contain any RAs, and thus, the RRT method was not used. These scenarios are mentioned here for comparison purposes.

VI. CONCLUSION

The research presented in this paper was borne out of the need to generate TCAS RAs within HITL simulated flights used for research and training. The RA issued by TCAS is highly sensitive to the trajectory of an intruder aircraft relative to the ownship flown by the pilot. Yet in realistic piloted simulations, the pilot must have full control over the ownship trajectory. Hence, using prescribed trajectories would not reliably result in the relative dynamics that lead to specific desired RAs. Moreover, the complexity of the TCAS logic and the dimensionality of the trajectory space require a novel method for mapping trajectories to the range of RAs generated by TCAS.

We applied an RRT algorithm to establish such a mapping between the space of relative trajectories and the space of TCAS RAs. The algorithm explores the space of intruder trajectories as defined by multiple 6-D waypoints (three dimensions for position and three dimensions for velocity). The TCAS logic evaluates the different intruder trajectories relative to the ownship and issues the relevant RA, should any be required. The mapping is used to select the trajectory waypoints most likely to result in specific RAs.

Such waypoints corresponding to a desired RA must be converted into trajectories flown by intruder aircraft during the HITL simulation. For the purpose of improving the simulation fidelity, intruder aircraft must adhere to realistic flight dynamics. To that end, the intruder guidance is designed to enable a robust implementation of traffic scenarios even as the ownship has nominal deviations from nominal conditions based on the pilot's input, without permitting the intruder aircraft to behave unrealistically. Experimental testing shows that the RRT method provides faster, easier, more generalizable, and more robust results without requiring particular expertise, relative to manual parameterization, which is slow, tedious, and comes after a trial and error process specific to each traffic circumstance.

By demonstrating robustness and ease of use, the results from piloted simulations highlight the potential of this method for pilot training and for research and development where pilots' reactions to TCAS RAs are of interest. Finally, mapping the relation between trajectories and RAs provides a high-level understanding of the topology implicit to the TCAS logic. Such notions estimate the probability that relative aircraft trajectories would result in one RA rather than another.

Applications include developing customized, focused exercises for pilot training, studying the effect of future ACAS X developments involving additional and novel types of aircraft, or improving airspace design by anticipating possible cascading conflicts resulting from compliance to RAs in high-density regions.

The authors acknowledge that the initial TCAS RA is only one part of TCAS behavior that is of interest. Perhaps even more important is the subsequent sequence of RAs that may strengthen or modify the original RA. In future extensions of this study, the authors are planning to add a third waypoint to the intruder trajectory, thereby gaining control on the progression of the RA. While the dimensionality of the trajectory space increases linearly as new waypoints are added (and the number of possible trajectories increases exponentially), RRT is an efficient method for rapid exploration of the space. The authors fully expect the algorithm to continue to provide useful results. However, in contrast to the initial RA where some bounds on the behavior of the ownship can

be assumed, here the progression of the RA is strongly determined by the ownship behavior. Therefore, the definition of intruder trajectory relative to that of the ownship should help to achieve reliability.

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