CONFLICT DETECTION AND ALERTING IN A SELF CONTROLLED TERMINAL AIRSPACE

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Abstract

A method for Conflict Detection and Alerting (CD&A) was developed as part the Small Aircraft Transportation System, Higher Volume Operations (SATS HVO) program at NASA Langley Research Center. The method addresses the specific problems and conditions of the concept of operations and uses a combination of state vector and procedure-based intent for conflict detection. The SATS HVO concept of operations has been developed to operate in small airports at self controlled terminal areas in near all-weather conditions. The concept uses vehicle-to-vehicle self-separation logic and centralized ground based sequencing. The self controlled area (SCA) is a volume surrounding a SATS airport where pilots accept responsibility for self-separation. Flights operating in the SCA, during instrument meteorological conditions (IMC), are given approach sequencing information computed by a ground based automated system referred as the Airport Management Module (AMM). All participating aircraft must be Automatic Dependent Surveillance-Broadcast (ADS-B) equipped and able to communicate with the AMM.

This paper proposes an innovative conflict detection method that combines linear state projections and intended approach paths based on the concept of aircraft conformance to a published procedure. The conflict alerting logic implements a multi-stage, non-symmetrical technique, also based on the conformance concept, that determines the order and time in which aircraft are notified of an impending conflict.

Preliminary batch simulation results have shown that the proposed CD&A technique is as effective as a purely state based logic but issues significantly less false alarms. High fidelity batch simulations and human-in-the-loop experiments are underway to further assess the concept's performance.

1 Introduction

The objective of the *Small Aircraft Transportation System (SATS)* program is to address the capacity problem facing the National Airspace System by increasing access to thousands of public use airports in the United States during Instrument Meteorological Conditions (IMC). At these non-towered, non-radar airports, procedural separation enforces one operation at a time during periods of IMC. The concept of operations developed for the *Higher Volume Operation (HVO)* element of the SATS program enables multiple concurrent operations at non-tower, non-radar airports during IMC.

The SATS HVO concept relies on the establishment of a newly defined area of flight operations called a Self Controlled Area (SCA). The SCA is a block of airspace around SATS designated airports during periods of IMC. Aircraft flying enroute to a SATS airport are on a standard IFR flight plan with Air Traffic Control (ATC) providing separation services. Within the SCA, pilots take responsibility for separation from other SATS aircraft using onboard equipment and procedures. Approaching aircraft get access to the SCA by requesting sequencing information from the ground based automation system referred as the *Airport Management Module (AMM)*. All participating aircraft must be Automatic Dependent Surveillance-Broadcast (ADS-B) equipped and able to communicate with the AMM. Procedural rules during normal operations enable safe separation from traffic and, therefore, conflicts due to loss of separation are precluded. The onboard conflict detection and alerting (CD&A) functionality provides an added degree of safety in case of non-normal conditions such as path deviations, procedure errors, etc.

Kushar and Yang present in [11] a survey of conflict detection and resolution algorithms and develop a detection and resolution classification scheme. In [9], Hoekstra et al. describe a modified potential algorithm in which aircraft have particle-like behavior with repulsive forces to keep aircraft separated. Bilimoria presents a two dimensional geometric optimization algorithm in [3]. Dowek, Geser, and Muñoz [7] have developed a 3 dimensional optimized geometric algorithm with a formal mathematical proof of its correctness. Probabilistic conflict detection is presented in [10]. Tomlin, Pappas and Sastry give a study of multi-agent hybrid systems for conflict resolution. Most of these techniques are applicable to unconstrained or loosely constrained enroute environments. For example, the conflict detection and resolution (CD&R) system presented in Ballin et al. [2] provides crews with tactical and strategic resolution advisories in a moderately constrained environment. These constraints include special use airspace, weather conditions, aircraft performance limitations, traffic, and others. However, when applied to highly constrained airspace such as the SCA, these enroute conflict detection techniques have been shown to be ineffective. Preliminary experiments by the authors using enroute algorithms in the terminal area resulted in a high number of false alarms and small lead time when a conflict is detected.

The conflict detection technique developed for SATS HVO operations in the SCA addresses these limitations of enroute conflict detection methods. The proposed technique uses a combination of state vector and intended approach path projection to predict potential loss of separation conflicts. Preliminary results show no missed conflicts and a very low number of false alerts compared to a state projection only.

The alerting logic is based on an asymmetrical alerting scheme. Although two aircraft running the CD&A algorithm will detect a conflict simultaneously, one aircraft might receive an alert before the other, based on their path conformance and aircraft lead/trail relation.

The hybrid conflict detection, the asymmetrical alerting, the nominal approach path, and the path conformance concepts will be discussed in detail in the next sections. The SATS HVO concept does not yet incorporate conflict resolution which is still under investigation by the authors.

2 Overview of SATS HVO Concept of Operations

The main components of the SATS HVO concept are:

- A set of operational rules to be followed by participant aircraft.
- A specially designated airspace called the *Self Controlled Area (SCA)*, where pilots assume responsibility for spacing and separation during IMC.
- A ground based automation system for access and sequencing called the *Airport Management Module (AMM)*.
- Onboard navigation tools and positioning system.
- Air-ground and air-air data communication such as Automatic Dependent Surveillance Broadcast (ADS-B).
- Navigation displays with traffic and alerting information.

The SATS approach procedure follows a generic RNAV GPS-T approach [8]. The structure and configuration of the SCA is defined for

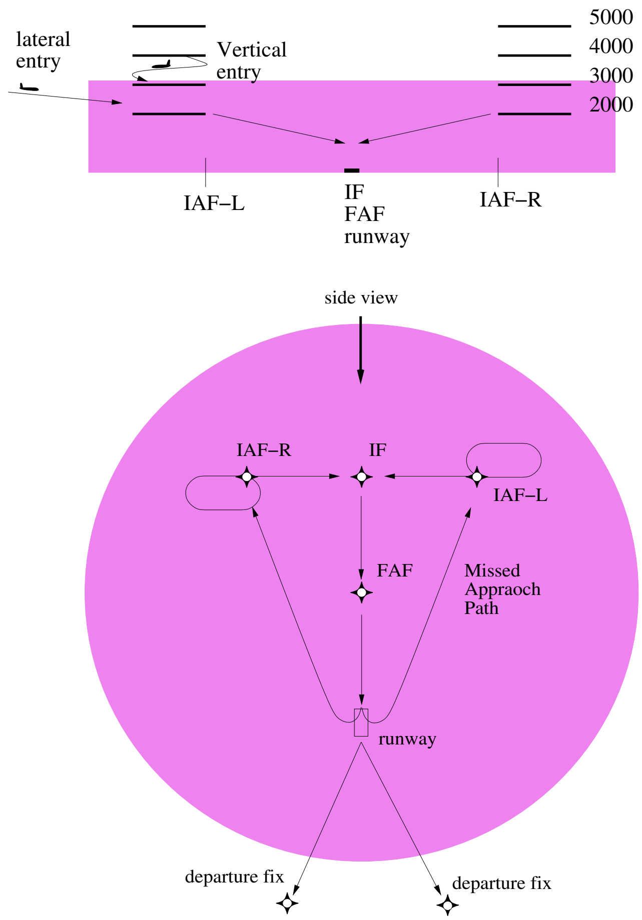

Fig. 1 Self Controlled Area, Side and Top Views

each specific airport environment. Figure 1 illustrates a generic SATS approach and a top and side view of a self controlled area (SCA).

The AMM is a ground based automated system that provides sequence information to participating aircraft and limits the number of concurrent approach operations in the SCA. The AMM functions include:

- Granting or denying entry into the SCA.
- Assigning a relative landing sequence to arriving aircraft.
- Assigning a missed approach holding fix to arriving aircraft.

There are two types of entry into the SCA: *vertical entry* and *lateral entry*. In low density traffic conditions, a lateral entry is usually given. In this case, the aircraft descends to the Initial Approach Fix (IAF) and initiates the approach as indicated by the published approach procedure and the sequence given by the AMM. In a vertical entry, an aircraft flies to the initial approach fix and holds at an altitude above the Self Controlled Area. When entry is granted by the AMM, the aircraft descends into the Self Controlled Area and holds at the lowest available altitude.

If an entry is granted by the AMM, the aircraft receives the follow notification and the missed approach holding fix assignment. The follow notification is either *none*, if it is the first aircraft in the arrival sequence, or the identifier of the preceding aircraft. The aircraft may initiate the final approach after some spacing criteria with respect to the lead aircraft are satisfied. In case of a missed approach, the aircraft flies over the missed approach point (MAP) and proceeds to its assigned missed approach holding fix (MAHF) according to the published procedure.

Departure fixes are outside the SCA. Hence, prior to a departure, aircraft must request clearance from Air Traffic Control. After clearance is granted and the aircraft is ready for departure, the departing aircraft monitors the arrival stream for a departure slot, defined as a clear runway and no aircraft past the final approach fix (FAF).

3 Nominal Approach Path and Path Conformance

A *nominal approach path* (NAP) consists of the approach segments that lead the aircraft through the approach fixes (IAF, IF, FAF, MAP) and to the runway threshold. The first segment of the path starts at the IAF and the last one ends at the runway threshold. For each one of the segments there is an intended speed profile range, spacing conditions, and a containment volume with lateral and vertical constraints.

The *containment volume* (CV) that surrounds the nominal approach path limits the accepted deviation of an aircraft from its nominal approach path. The exact shape and dimensions of the containment volume is still under research. For a nominal SCA, the containment volume of a holding pattern extends $\pm H_{cv}$ feet vertically from the holding altitude and $\pm D_{cv}$ nautical miles horizontally from the oval defining the holding pattern. For the T approach, the containment volume extends $\pm H_{cv}$ feet vertically and $\pm D_{cv}$ nautical miles horizontally from the 3 dimensional linear segments formed by the base, intermediate and final segments. The concept of operations loosely constrain the trajectory of aircraft flying a lateral entry, a missed approach, or a departure. Hence, the containment volume for lateral entry zones, missed approached zones, and departure zones is undefined.

An aircraft in the SCA is said to be *in conformance* with its NAP if it satisfies all the segment's conditions which includes: remaining in the containment volume, compliance to speed profiles, and maintaining spacing constraints. Path conformance is monitored by the onboard automation logic throughout SATS operations. Since the NAP is based on published procedures, the NAP represents the *implicit intent* of every participating aircraft in the SCA. Therefore, if an aircraft is *in conformance*, it is possible to predict its intended path based on the NAP and its current state vector.

Implicit intent is different from *intent* as regularly defined in CD&R studies such as [2, 6, 12, 13, 14]. In these cases, an aircraft intent is not known to others and needs to be communicated, usually in the form of trajectory change points (TCP). We refer to this technique as explicit intent.

4 Conflict Detection

Conflict detection is accomplished by predicting the future location of aircraft within a given look ahead time. *State based* CD&R algorithms [3, 7, 9] use linear projection of the 3 dimensional position and velocity vector to predict the trajectory of an aircraft.

State based algorithms provide *tactical* predictions as they rely solely on the current state of the aircraft. *Intent based* algorithms [2, 6, 12, 13, 14] are more *strategic* in that they use intent as well as state information to predict the future position of an aircraft. Intent information is usually given as a list of way points and exchanged between aircraft via data link.

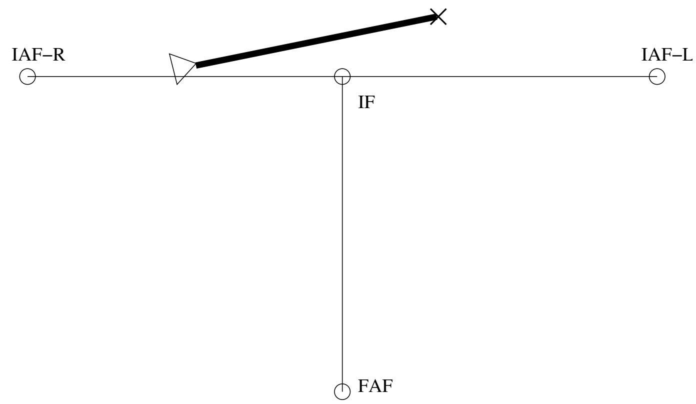

Fig. 2 State Based Projection

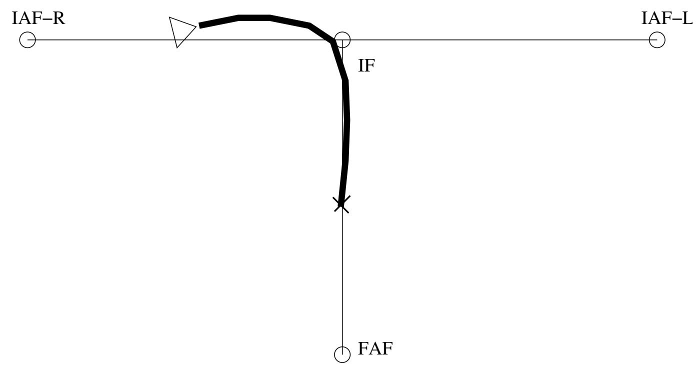

Fig. 3 NAP Implicit Intent Based Projection

This paper describes a hybrid approach to conflict detection that uses linear state projection and *implicit* intent information. As explained in the previous section, the intended path is derived from the aircraft nominal approach path (NAP).

Figures 2 and 3 illustrate the two path prediction methods: state and NAP based respectively. In the state based projection, the future location of the aircraft (indicated with an X) is calculated using the current position, heading, horizontal speed, and vertical speed, i.e., position and velocity vector, of the aircraft. The NAP based projection uses the state of the aircraft to predict a trajectory that adheres to its nominal approach path. Curved trajectories are approximated by a series of linear segments.

The pair-wise *hybrid conflict detection* algorithm selects a path projection technique for the ownship and each traffic aircraft. A NAP based projection is used for all aircraft in path conformance. A state based flight path projection is used for aircraft not in conformance, flying a lateral entry, flying a missed approach, or flying a departure.

The *protected zone* of an aircraft is a cylinder of diameter D and height H, centered at the aircraft current position. A *conflict* is defined as a projected separation of less than D nautical miles horizontally and H feet vertically. A *violation* (or a *loss of separation*) is an overlap of the protected zones of two aircraft.

Based on the trajectory predictions, the algorithm computes a *time interval of conflict* $[t_{in}, t_{out}]$, where t_{in} is the time to loss of separation and $t_{out} - t_{in}$ is the projected time length of the conflict. If $t_{in} > 0$ then a loss of separation will occur in the future in t_{in} units of time. If $t_{in} \leq 0$ and $t_{out} \geq 0$, the aircraft are currently in violation.[1] In any other case, the aircraft are not predicted to be in conflict.

The rational for this hybrid trajectory prediction technique is that an aircraft in path conformance is much more likely to be well behaved and follow the intended path. No assumptions should be made of an aircraft which is out of conformance. The objective of this approach is to minimize false alerts and effectively predict potential conflicts in both state and intent based paths.

5 Conflict Alerting

The conflict alerting algorithm developed for SATS HVO employs a multi-stage, asymmetrical alerting scheme. *Multi-stage* refers to the use of two levels of alerts, *cautions* and *warnings*, depending upon the time to conflict. Asymmetrical refers to the use of a time delay to display an alert depending on the path conformance status and leading/trailing relationship of the two conflicting aircraft.

The multi-stage logic is based on the time to loss of separation t_{in}. To accommodate small navigation errors and GPS inaccuracies, the alerting algorithm filters away conflicts where the time interval $[t_{in}, t_{out}]$ is small, i.e., where $t_{out} - t_{in}$ is less than a configurable small time T_ε. Caution and warning alerts are selected by comparing the time to conflict t_{in} to caution and warning look ahead times, T_c and T_w, respectively.

- If $T_w < t_{in} \leq T_c$, the alerting logic selects a *caution*.
- If $t_{in} \leq T_w$, the alerting logic selects a *warning*.
- If $t_{in} \leq 0$ the warning is also a *violation*.

Two conflicting aircraft, running the same CD&A algorithm, detect the impending conflict at the same time.[2] Furthermore, the time interval $[t_{in}, t_{out}]$ is the same for both aircraft. The alerting logic, however, does not immediately issue an alert after a conflict is detected. The alert of an aircraft that is in path conformance is delayed a configurable small time T_{conf} after a conflict is detected. If both aircraft are in path conformance and they are in a leading/trailing relationship, the alert of the lead aircraft is delayed a configurable small time T_{lead}.

This logic permits a conflicting aircraft that is out of conformance (or trailing) to make trajectory and speed adjustments to correct its course, and then, to resolve the conflict, before the aircraft that is in conformance (or leading) is notified.

6 Experimental Study

The hybrid conflict detection and alerting algorithm has been evaluated and compared with state based conflict detection. To that end, a low fidelity simulation environment called SOFIE (**S**ATS-HVO L**o**w **Fi**delity **E**nvironment) was developed. The simulation environment provides:

[1] By convention, $t_{in} = t_{out} = 0$ is the case of parallel conflicting trajectories.

[2] Within a delta time depending on the execution rate of the algorithms and no more than one execution cycle.

- A low fidelity model of aircraft kinematics, where aircraft are represented as points in a 3-D space with a velocity vector.
- Two type of aircraft performance and several ranges of initial and final approach speeds.
- Path deviations, modeled by random uniform errors in speed, heading, and altitude.
- Pseudo-randomly generated traffic that includes arrivals, departures, and missed approach operations.
- A basic model of Air Traffic Controller that enables the transition from enroute to the SCA. The simulated ATC assigns holding altitudes outside the SCA and handles the transitions between holding altitudes outside the SCA.
- Prototype implementations of the AMM, path conformance, conflict detection, and alerting logic presented in this paper. These implementations conform to the high-level specification of the functionality described in [4] and [1].
- An interface for batch and interactive simulation that enables different settings of configurable variables.

6.1 Experiments

The primary goal of the experiments was to compare the SATS HVO CD&A logic to a purely state based logic, with respect to false and missed alarms, for different configurations of protected zone and look ahead times. In the context of these experiments, *false alarms* are defined as alerts issued by the CD&A logic without a subsequent violation. Conversely, *missed alarms* are violations without a preceding alert being issued.

The experiments cover 5 periods of 12 hours of operations in the vicinity and inside a nominal SCA. Traffic data, which include arrivals, departures, and missed approaches, were pseudo-randomly generated using the following uniform distributions:

- Arrivals: 4 per hour of operations.
- Departures: 2 per hour of operations.
- Missed approaches: 1 per 8 arrivals.

These distributions were chosen to exercise the CD&A algorithm. They do not correspond to actual distributions of traffic, nor do they illustrate traffic projections of a typical SATS airport.

On top of the aircraft kinematic model, SOFIE introduces path deviations that model navigation errors incurred by aircraft following a nominal path. These deviations are bounded and modeled by uniform distributions. The simulated operations included conflict geometries where not all aircraft were in conformance.

SOFIE does not implement resolution maneuvers for aircraft in conflict. This allows for a precise counting of false alarms. Furthermore, for completeness, SOFIE implements a state based CD&A logic for aircraft outside the SCA. However, only alarms that are issued inside the SCA are counted.

The 5 data sets, named A to E, are summarized in Table 1. State and hybrid logics are exercised and compared over the same data sets (A to E) for different values of D, H, T_c, and T_w. Five configurations are considered:

1. Large protected zone, long look ahead times: $D = 3$ nautical miles, $H = 750$ feet, $T_c = 120$ seconds, $T_w = 30$ seconds.
2. Large protected zone, short look ahead times: $D = 3$ nautical miles, $H = 750$ feet, $T_c = 45$ seconds, $T_w = 20$ seconds.
3. Small protected zone, long look ahead times: $D = 1$ nautical mile, $H = 300$ feet, $T_c = 120$ seconds, $T_w = 30$ seconds.
4. Small protected zone, short look ahead times: $D = 1$ nautical mile, $H = 300$ feet, $T_c = 45$ seconds, $T_w = 20$ seconds.
5. Very small protected zone, very short look ahead times: $D = 0.35$ nautical miles, $H =$

Data Set	Arrivals	Departures	Missed Appr.
A	40	32	7
B	48	31	4
C	59	24	8
D	54	22	6
E	53	29	9
Avg	50.8	27.6	6.8
Avg/hour	4.23	2.3	0.57

Table 1 Data Set Experiments (12 Hours)

400 feet, $T_c = 35$ seconds, $T_w = 20$ seconds.[3]

	Configuration	CD&A	False Alarm Ratio
1	$D = 3, H = 750,$ $T_c = 120, T_w = 30$	Hybrid	49%
		State	69%
2	$D = 3, H = 750,$ $T_c = 45, T_w = 20$	Hybrid	32%
		State	58%
3	$D = 1, H = 300,$ $T_c = 120, T_w = 30$	Hybrid	30%
		State	61%
4	$D = 1, H = 300,$ $T_c = 45, T_w = 20$	Hybrid	10%
		State	59%
5	$D = 0.35, H = 400,$ $T_c = 35, T_w = 20$	Hybrid	0%
		State	0%

Table 2 False Alarm Ratio

6.2 Results

In all the configurations, hybrid and state only logics are well behaved with respect to missed alarms, i.e., they do not fail to issue an alert before a violation. In other words, in both approaches, all conflicts that lead to a violation were detected.

Table 2 summarizes the results of the experiments for false alarms where data sets A-E have been averaged into each configuration. It shows, for each configuration, the average ratio of false alarms compared to the total number of alerts. The smaller the ratio, the more effective is the logic to avoid false alarms. The hybrid logic is consistently better than the state only logic in the first four configurations. For instance, for a small protected zone and short look ahead times (configuration 4), only 10% of alarms issued by the hybrid logic are false alarms. For the same configuration, the percentage of false alarms issued by the state only algorithm is 59%. In all configurations, the average ratio of false alarms issued by the hybrid logic is less than 50% and it decreases as the protected zone is reduced and the look ahead times are shortened. Except for the case of a very small protected zone and very short look ahead times, the average ratio of false alarms issued by the state only algorithm is always greater than 50%.

Configuration 5 corresponds to an extreme case of a very small protected zone ($D = 0.35$ nmi, $H = 400$ feet) and very short look ahead times ($T_c = 35$ sec, $T_w = 20$). This kind of setting is typical of collision avoidance systems such as Traffic Collision Avoidance System (TCAS) [5]. In this case, both algorithms avoid false alarms. However, there are significant safety issues to consider in this configuration when used in a terminal aerospace.

Table 3 summarizes minimum and average time when an alarm was issued prior to a loss of separation and average and minimum horizontal traffic distance when an alarm was issued prior to a loss of separation. Data sets A-E have been averaged into each configuration. The greater the numbers in the table, the longer time the pilot has to implement a resolution maneuver and the farther the aircraft are. As expected, these numbers are closely related to the size of the protected zone and the look ahead times. In the first four configurations, the hybrid approach is consistently better than the state only approach. For a small protected zone an a short look ahead time (configuration 4), the average time to loss of separation is 44 seconds for the hybrid approach and 14 seconds for the state only approach. This means that, in average, the hybrid approach pro-

[3] These numbers roughly correspond to TCAS for 2500 feet above ground level and below.

Configuration		CD&A	Time [sec]		Distance [nmi]	
			Min.	Avg.	Min.	Avg.
1	$D = 3, H = 750$, $T_c = 120, T_w = 30$	Hybrid	9	78	3.1	4.5
		State	5	50	2.3	4
2	$D = 3, H = 750$, $T_c = 45, T_w = 20$	Hybrid	9	40	3	3.8
		State	6	33	2.4	3.6
3	$D = 1, H = 300$, $T_c = 120, T_w = 30$	Hybrid	20	105	1.1	2.2
		State	8	31	0.9	1.4
4	$D = 1, H = 300$, $T_c = 45, T_w = 20$	Hybrid	20	44	1	1.4
		State	4	14	0.9	1.1
5	$D = 0.35, H = 400$, $T_c = 35, T_w = 20$	Hybrid	34	34	0.5	0.7
		State	34	35	0.5	0.7

Table 3 Time and Distance to Loss of Separation

vides additional 30 seconds of lead alert time before loss of separation. In this case, the average horizontal separation with the traffic aircraft was 1.4 nautical miles at the time when the hybrid CD&A algorithm issued the alarm. The average for the same configuration was 1.1 nautical miles when the state based algorithm was used. For configuration 5, the average time to react before an eventual loss of separation is 34 seconds and the average aircraft separation when the aircraft first receive an alert is 0.75 nautical miles.

7 Conclusion

CD&A algorithms are designed to keep a safety balance between missed and false alarms. *Missed alarms*, defined as the absence of alerts prior to a loss of separation, are an obvious safety concern to CD&A system designers. *False alarms*, i.e., alerts that are issued without a subsequent loss of separation, are an annoyance to the crew. They can also have a detrimental impact on the overall safety of the system as pilots will tend to disregard or disengage the alerting system.

The SATS HVO CD&A logic was designed to cope with the highly constrained environment of a nominal SATS terminal area. An early decision made by the SATS HVO CD&A design team was to minimize the number of false alerts while providing adequate warning to the pilot. The algorithm that was finally proposed uses a *hybrid approach* where state and implicit intent path projections are combined. The intent path projection is based on the published T approach procedures in the Self Controlled Area (SCA) and the SATS HVO concept of operations. If an aircraft trajectory is within predetermined bounds of the nominal approach path, then the intended path is used to predict the aircraft trajectory. If an aircraft deviates more than a predetermined threshold from the nominal approach, then this aircraft is no longer expected to follow its intended path; the hybrid algorithm reverts to a state based conflict detection.

Experiments on a low fidelity simulation environment have shown that hybrid and state only logics performed perfectly well with respect to missed alarms. However, for a protected zone 1 nautical mile or greater, the hybrid approach issued consistently fewer false alarms than the state only approach. In contrast to the hybrid approach, more than half the number of alerts issued by the state only logic in these configurations are false alarms.

For a configuration of a very small protect zone (0.35 nautical miles of diameter) and very short look ahead times (20 seconds), hybrid and state base CD&A logics behave in a similar manner with respect to false alarms. However, this extreme configuration raises significant safety concerns to be investigated using human factors techniques and pilot in the loop experiments.

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Acronyms

ADS-B	Automatic Dependent Surveillance Broadcast
AMM	Airport Management Module
ATC	Air Traffic Control
CD&A	Conflict Detection and Alerting
CD&R	Conflict Detection and Resolution
CV	Containment Volume
FAF	Final Approach Fix
GPS	Global Positioning System
HVO	Higher Volume Operations
IAF	Initial Approach Fix
IF	Intermediate Fix
IFR	Instrument Flight Rule
IMC	Instrument Meteorological Conditions
MAHF	Missed Approach Holding Fix
MAP	Missed Approach Point
NAP	Nominal Approach Path
NASA	National Aeronautics and Space Administration
SATS	Small Aircraft Transportation System
SCA	Self Controlled Area