NASA/TM-2002-211963

Evaluation of a Pair-Wise Conflict Detection and Resolution Algorithm in a Multiple Aircraft Scenario

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December 2002

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

December 2002

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Evaluation of a Pair-Wise Conflict Detection and Resolution Algorithm in a Multiple Aircraft Scenario

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Abstract

The KB3D algorithm is a pairwise conflict detection and resolution (CD&R) algorithm. It detects and generates trajectory vectoring for an aircraft which has been predicted to be in an airspace minima violation within a given look-ahead time. It has been proven, using mechanized theorem proving techniques, that for a pair of aircraft, KB3D produces at least one vectoring solution and that all solutions produced are correct. Although solutions produced by the algorithm are mathematically correct, they might not be physically executable by an aircraft or might not solve multiple aircraft conflicts. This paper describes a simple solution selection method which assesses all solutions generated by KB3D and determines the solution to be executed. The solution selection method and KB3D are evaluated using a simulation in which N aircraft fly in a free-flight environment and each aircraft in the simulation uses KB3D to maintain separation. Specifically, the solution selection method filters KB3D solutions which are procedurally undesirable or physically not executable and uses a predetermined criteria for selection.

1 Introduction

Free-flight[8] is a concept in which aircraft crews have more autonomy and part or all of the responsibility for airborne traffic management and separation assurance has been transfered from ground based control to a distributed cockpit based control. Conflict detection and resolution algorithms is a key enabling technology for free-flight. The KB3D algorithm is a 3 dimensional conflict detection and resolution algorithm (CD&R) developed by Dowek, Muñoz, and Geser[3]. It is an extension and optimization of Billimoria's 2 dimensional CD&R algorithm[2].

Airborne based CD&R algorithms are used to maintain separation between their own aircraft (the aircraft where the algorithm is running) and all surrounding aircraft. Therefore, the algorithm must have access to pertinent information about all surrounding aircraft. Several systems[10, 7, 9] are being proposed to accomplish information exchange amongst aircraft in a free-flight environment. These systems will not be discussed in this paper.

Conflict detection and resolution algorithms can be broadly classified as state based or intent based. State refers to the current physical parameters of the aircraft such as location, altitude, and vertical and ground speeds. Intent refers to future maneuvers the aircraft will perform such as change of trajectories at waypoints. Intent parameters usually reside in a flight management computer or similar device.

The KB3D algorithm is a state based CD&R algorithm. The detection part of the algorithm projects the state of its own aircraft and the state of each of the traffic aircraft and determines if an airspace conflict exists in the future within a given lookahead time. If a future conflict exists, the resolution part produces solutions which will change the trajectory of the own aircraft to avoid the conflict. A unique feature of the KB3D algorithm is that it has been mathematically shown to produce at least one solution for every conflict pair and that all solutions produced are correct solutions. That is, a correct solution solves the conflict. The proof of correctness was checked using mechanized theorem proving[6].

Although KB3D has been shown to produce mathematically correct solutions, these solutions are not always physically executable or operationally desirable. Also, both the detection part and the resolution part of the algorithm are pair-wise detection and resolution. For N aircraft in a give airspace, the algorithm performs detection and resolution between itself and each of the other N-1 aircraft. In general, resolution of conflicts may not be compositional; the resolution of one conflict pair can negatively affect the resolution of another pair.

In order to assess the suitability of the solutions, the effectiveness of the algorithm, and the performance of a pair wise CD&R algorithm in a multiple aircraft scenario, an evaluation simulation was developed. In the simulation, N aircraft fly on random trajectories in a cubical shape, size selectable, airspace volume. On each aircraft in the simulation, the KB3D algorithm is used to detect conflicts and generate conflict solutions and a solution selection logic is used to select which of the solutions will be executed.

2 Simulation

The simulation environment was created for the evaluation of en-route free-flight concepts. The simulation described in this paper does not make use of human test subjects. Control commands produced by algorithms are directly used to control the aircraft in the simulation. Extensive studies and simulations where airline pilots participate as test subjects are also being used for the evaluation of free-flight concepts and have been reported in [1].

One advantage of evaluating a CD&R algorithm using a pilot-less simulation is that the algorithm can be implemented in hundreds of aircraft and run for hundred or thousands of hours. Such an extended simulation would not be economically practical using human test subjects.

The simulation is written in Java and platform independent. It uses a very simple 3 dimensional kinematics model for the aircraft. The number of aircraft, the dimensions of the airspace, simulation duration, and other parameters, are user selectable. For the results presented in this paper, the horizontal dimensions were set to 200 by 200 nautical miles and the vertical dimension to 32 thousand feet (18 to 50 thousand feet).

During a simulation run, the number of aircraft the user selects remains constant. This is accomplished by replacing aircraft which exit the airspace with new aircraft entering the airspace. Aircraft enter the airspace at random points through five of the six surfaces enclosing the airspace. Aircraft can exit the airspace through the top surface but do not enter through the top surface. Another restriction on randomly entering aircraft is that they are not in conflict or airspace violation with any of the existing aircraft at the time of entry.

When starting a simulation, the user can determine how the aircraft will be initialized. The user can create an initialization file with the state of each aircraft at time zero or can call a random initialization function. The user can also partially initialize the aircraft and the rest will randomly enter the airspace. The state of an aircraft is defined by the 11 parameters in table 1.

x	location, easterly direction	nautical miles
y	location, northerly direction	nautical miles
z	altitude	thousand of feet
gs	ground speed	knots
trk	direction of motion	degrees 0 - 359.99... clockwise from north
vs	vertical speed	feet per minute
des_x	destination, easterly direction	nautical miles
des_y	destination, northerly direction	nautical miles
des_z	destination altitude	thousand of feet
eta	Estimated time of arrival	seconds
conf	Status of conflict	0, 1, or 2

Table 1: Aircraft States

The simulation runs in a time loop from zero to the time selected by the user. The time step of the simulation is one second. In each time step, the simulation updates the position of the aircraft, checks for airspace violations, and uses a selected CD&R algorithm on each aircraft to maintain separation. The KB3D algorithm, through a filtering, selection, and limiting function described in the next section, is evaluated using the simulation.

3 The KB3D Algorithm

KB3D has some computational advantages over similar CD&R algorithm. The KB3D implementation does not have loops in the code; therefore, termination is guaranteed. The code does not make use of transcendental functions such as tangent and arctangent; only basic arithmetic functions and square root are used in the computation. The KB3D algorithm does not have singularities in its computational space which other CD&R algorithms have, such as the modified voltage potential algorithm [4]. KB3D is currently implemented in Java but could easily be translated to other languages such as c++.

KB3D is a pair-wise CD&R algorithm. For a given pair of aircraft, an aircraft executing the CD&R algorithm considers itself the *ownship* and it considers the other aircraft the *intruder*. The solutions generated by the algorithm on the ownship solve the conflict without any change to the intruder's projected trajectory. If the intruder is also running a CD&R algorithm, a less aggressive maneuver might be necessary to avoid the conflict. All aircraft in the simulation run the KB3D algorithm. In one simulation step, each aircraft runs the CD&R algorithm against all other $N-1$ aircraft in the airspace. Therefore, the algorithm is executed $N(N-1)$ per simulation step. Multiple conflicts are handled in a naive way. For example, if an aircraft detects and starts executing a resolution maneuver and subsequent conflicts are detected, the resolution of the subsequent conflicts can override the first resolution. This is one of the objectives of the experiment: to evaluate the performance of a pair-wise CD&R algorithm in a multiple conflict scenario. Heuristics are being investigated on how to minimize or eliminate the creation of new conflicts resulting from the resolution of a previous conflict. These heuristics will be incorporated and evaluated in future experiments.

The algorithm depends on the assumption, when computing the solutions, that for a given pair of aircraft, the ownship is not inside the protected zone of the intruder. Once the ownship is inside the protected zone (space minima violation), the algorithm no longer produces solutions to maintain separation. An aircraft that enters the protected zone of another aircraft can continue indefinitely on a trajectory which produces a separation minima violation. This behavior is reflected in the experiment results discussed in the next section. It is expected that integrated cockpits implementing airborne separation assurance will have additional capabilities to handle scenarios where loss of separation minima has occurred, such as collision avoidance.

The KB3D algorithm produces at least one solution and up to 6 solutions. Solutions produced by KB3D are for three different aircraft parameters: ground speed change, vertical speed change, and track (horizontal direction) change. Each of this solutions, when independently implemented, will avoid the conflict. Therefore, in an operational environment, one of the algorithm's multiple solutions should be selected for conflict resolution.

For the experiment, selection of the solution is performed using the decision flow chart of Figure 1. The selection method is the result of: 1. early observations of free flight simulations; 2. preference of flight crews; and 3. how efficiently the maneuver can be executed. It was observed that, in scenarios with typical National Airspace densities, most horizontal change maneuvers only required a few degrees of change to solve the conflict. Another consideration in the solution selection process is the expected in-route altitude of aircraft in free flight. In-route aircraft in free flight are expected to fly near their maximum altitude. Therefore, solutions where an aircraft must climb might not be physically possible. Solutions involving ground speed changes are the least favored amongst crews and are undesirable because the time required to execute a speed change is typically several time longer than the time to execute a track change or altitude change.

The solution selection process first checks the track solution for operational and physical limitations. If the track solution is within the physical and operational limits, it selects the smallest of the right or left turn. If the track change solution is not feasible or out of the operational limits, it checks for climb rate (vertical speed) and descent rate. If vertical speed solutions are also out of bounds, the algorithm checks the increase ground speed followed by the decrease ground speed.

When all of the solutions are outside of the established bounds, the selection algorithm selects the smallest of the right turn or left turn. This is the "never give up" selection. Note that although a solution might be physically possible, it might be initially rejected by the operational bound, which is a somewhat arbitrary bound (see Table 2).

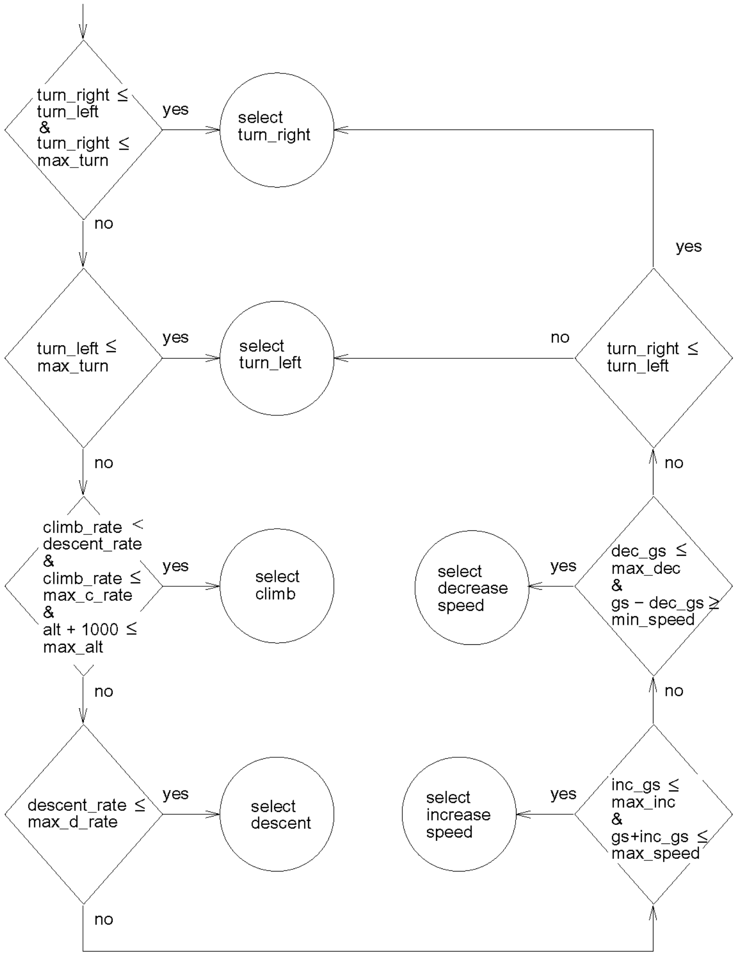

Figure 1: Solution Selection Logic

Once a solution is selected, it goes through a limiting function. For example, if the solution is to turn right by 10 degrees, the limiting function calculates the maximum turn rate to achieve the heading change. This is given by:

$$\mathit{max\ turn\ rate} = \frac{180 \cdot g \cdot \tan(\phi)}{\mathit{speed} \cdot \pi} \text{ degrees/second}$$

where g is the gravitational force, *speed* is the aircraft ground speed, and ϕ is the bank angle of the aircraft. Using a maximum bank angle imposed by operational constraints, the simulation then changes the heading of the aircraft at its maximum turn rate until the full heading change is accomplished.

The maximum rates and limits are set for a generic commercial aircraft and based on previous experiments or conversations with pilots. They are somewhat arbitrary. A more accurate simulation will have different types of aircraft with more characteristic parameters for each aircraft. The maximum altitude for resolution is the altitude at which a climb will not be use to resolve a conflict. Although an aircraft in the simulation can fly up to 50 thousand feet, the resolution algorithm will not command a climb if the aircraft is at 40 thousand feet or above. The parameters were set as shown in Table 2

max. altitude for resolution	40 thousand feet
max. vertical speed	2000 feet/minute
maneuver time	2% of conflict time
max. acceleration	1.42 knots/second (NM/hour-sec.)
max. deceleration	1.25 knots/second
max. ground speed	550 knots
min. ground speed	250 knots
max. speed increase	50 knots
max. speed decrease	100 knots
max. heading change	17 degrees
max. bank angle	35 degrees

Table 2: Operational and Physical Constraints

These numbers are fairly conservative and can be adjusted in future simulation to determine their impact on the performance of the CD&R algorithm. For the results presented in this paper, the objective is to evaluate the algorithm solutions and its performance in a multiple aircraft scenario with generic physical constraints.

4 Simulation Results

The simulations are performed in an airspace with dimensions of 200 by 200 nautical miles by 32,000 feet. The number of aircraft in the airspace is varied from 18 to 250 aircraft. Look ahead time for the CD&R algorithm is 5 minutes (300 seconds). The protected zone (separation minima) around an aircraft is a cylinder with a radius of 5 nautical miles horizontally and 1000 feet vertically over and below the aircraft. The detection part of the algorithm projects into the future the state of the intruder and own ship. A conflict is detected if one aircraft enters the protected zone of the other within the lookahead time. If an aircraft is inside the protected zone of another aircraft, an airspace violations has occurred and it is flagged by the simulation.

The duration of each simulation is 100 hours (360,000 seconds). Simulations have been performed on a Sun workstation running Solaris and on a Intel based PC running Linux. Figure 2 shows a graph of the number of conflicts as a function of number of aircraft. Eighteen aircraft in a 200 by 200 nautical miles airspace corresponds approximately to the traffic density over the continental United States in the year 1997. Fifty four aircraft in the same airspace is a figure used in previous experiments [5] as 3X (3 times) 1997 densities. The number of aircraft is increased past the 3X density to determine at what point the CD&R algorithm is no longer effective in maintaining separation in a free flight environment with aircraft flying random paths.

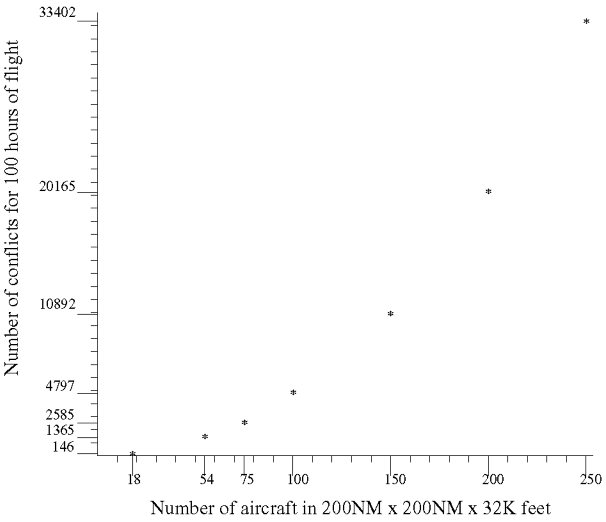

Figure 2: Conflicts as Function of Number of Aircraft

The relation of aircraft number n to conflicts per 100 hours, based on the results for 18 to 250 aircraft, is exponential and can be approximated by the equation,

$$\mathit{conflicts/100\ hours} = \frac{n^{2.06}}{2.65}$$

As long as all conflicts can be properly resolved without loss of separation minima, the number of conflicts is not a very relevant issue from the safety point of view. However, if resolution is being implemented by the crew, an increased number of conflicts can have an impact on crew workload and safety. It can also have an impact on scheduling, fuel efficiency, and computational requirements. The relation of aircraft number to conflicts gives insight into the airspace traffic complexity as the aircraft density increases. Using the 3X density, we can calculate the average number of conflicts per aircraft per hour to be 0.25. This means that for a one hour flight, the crew can expect to detect and resolve one conflict every fourth flight. For 200 aircraft, more than 10 times 1997 densities, the cockpit crew can expect an average of one conflict per one hour of flight. These conflict rates appear to be low and well within the capability of the crew to detect and resolve.

Figure 3 shows number of space violations (loss of separation minima) as a function of number of aircraft for 100 hours runs. A space violation occurs when an aircraft is less than 5 nautical miles horizontally *and* less than 1000 vertically from another aircraft.

All loss of separation minima recorded during simulation did not present a collision threat. The point of closest separation occurred during the 250 aircraft simulation and it

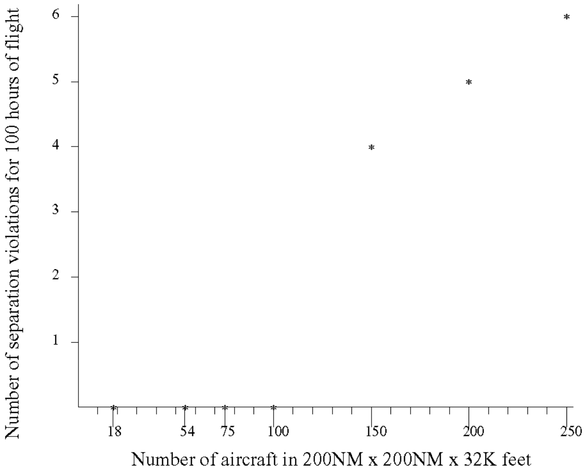

Figure 3: Separation Minima Violations as Function of Number of Aircraft

was 4.6506 nautical miles horizontally and 252 feet vertically. Tables 3, 4 and 5 summarize the characteristics of the loss of separation events. The closest separation was worst case. The average horizontal and vertical is the average of the closest distance during loss of separation.

Number of aircraft	150
Closest separation	4.868 n miles, horiz. 11 feet, vert.
Average horizontal	4.964 n miles
Average vertical	282 feet
Average duration	6.2 seconds

Table 3: Loss of Separation Summary: 150 aircraft

Although the separation minima violation data is not statistically significant to draw accurate conclusions, it appears that the severity of the violations is not affected by the increase in density from 150 to 250 aircraft. The number of violations appears to follow a linear relation. This is in contrast to the number of conflicts which grows exponentially with number of aircraft.

Violations range from 4.6501 nautical miles horizontally and 252 feet vertically to 4.9999 horizontally and 834 feet vertically. Several of the violations flagged by the simulation are of the type where the horizontal separation is 4.9999 nautical miles and the duration is only 1 second. These results suggest that by increasing the dimensions of the detection and resolution from 5 nautical miles to a slightly larger protection zone, for example 5.1 nautical miles, most of the violations could be eliminated.

We observed, when running 100 hours simulations, that there were no separation minima violations for densities of 100 aircraft or less. However, it is possible that for densities in the 100 aircraft range, violations are rare events but nevertheless exist. To

Number of aircraft	200
Closest separation	4.669 n miles, horiz. 431 feet, vert.
Average horizontal	4.925 n miles
Average vertical	571 feet
Average duration	12.6 seconds

Table 4: Loss of Separation Summary: 200 aircraft

Number of aircraft	250
Closest separation	4.650 n miles, horiz. 252 feet, vert.
Average horizontal	4.935 n miles
Average vertical	474 feet
Average duration	14.2 seconds

Table 5: Loss of Separation Summary: 250 aircraft

address this concern, the simulation was run for 1000 hours (41.6 days) and 100 aircraft. This is equivalent to 100,000 aircraft-flight-hours. The 1000 hours simulation with 100 aircraft gave 8 violations with the closest separation 4.840 nautical miles horizontally and 726 feet vertically. A simulation of 1000 hours with 54 aircraft gave no violations.

Finally, the effectiveness of conflict detection and resolution is illustrated by comparing two simulation runs, one with CD&R disabled and one with CD&R enabled. The results are given in table 6.

Number of aircraft	18	18
CD&R	disabled	enabled
Number of violations	81	0
Violation closest separation	0.212 n miles, horiz. 165 feet, vert.	na
Average horizontal	2.88 n miles	na
Average vertical	455.8 feet	na
Average duration	122.1 seconds	na

Table 6: Comparison of Simulation with CD&R Enabled and Disabled

5 Conclusion

The performance evaluation of the KB3D CD&R algorithm, augmented with a simple solution selection logic, gave some interesting preliminary results. The growth of conflicts is exponential. With 250 aircraft, the density is approximately one aircraft per 1000 cubic nautical miles. This is one aircraft per 10 nm x 10 nm x 10 nm cube. Around airports and other high congestion areas, densities could be much higher that this which could produce very high conflict rates for purely random flight trajectories and a state based CD&R. However, trajectories around airport follow define patterns and routes.

Fairly conservative maneuver limiting did not hinder good performance from the algorithm. For densities 3 times higher than 1997 North American densities (54 aircraft in the airspace volume), the system was able to resolve all conflicts with no separation minima violation for 100,000 aircraft-flight-hours. For approximately 5 times 1997 North American densities (100 aircraft in the airspace volume), 8 violations were observed for 100,000 aircraft-flight-hours.

All separation minima violations were benign in that aircraft never came closer than 4.8 nautical miles and the possibility of collision was almost non-existent. This result suggest that the CD&R algorithm thresholds parameters could be adjusted to practically eliminate violations for the space densities studied.

It was found that the pair-wise CD&R algorithm performed very well in a multiple aircraft scenario even when a naive resolution selection logic was used. A more discerning selection logic, under development at this time, could also reduce or eliminate separation violations. Future experiments will incorporate these changes and measure their impact. Also being studied is the impact of a resolution on an aircraft nominal trajectory, estimated time of arrival, fuel burn, and other performance parameters.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 12-2002	**2. REPORT TYPE** Technical Memorandum	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE
Evaluation of a Pair-Wise Conflict Detection and Resolution Algorithm in a Multiple Aircraft Scenario

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Carreño, Víctor A.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
727-01-26-01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-18252

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TM-2002-211963

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 03
Availability: NASA CASI (301) 621-0390 Distribution: Nonstandard

13. SUPPLEMENTARY NOTES
An electronic version can be found at http://techreports.larc.nasa.gov/ltrs/ or http://techreports.larc.nasa.gov/cgi-bin/NTRS

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15. SUBJECT TERMS
Conflict detection; Conflict resolution; Free flight; Simulation

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
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