A GEOMETRIC ALGORITHM FOR THE CALCULUS OF MULTIDIMENSIONAL AIRBORNE CONFLICT RESOLUTION TRAJECTORIES

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Abstract

This article describes the calculus, instruction and operational conduction of air traffic conflict resolution maneuvers. A so called “air traffic conflict” shall define a situation, in which, according to projections of their flight paths, one or more aircraft are predicted to be situated inside a collision avoidance zone of a defined shape (e.g. cylinder) that is virtually placed around some other aircraft. The resolution of a traffic conflict is achieved via proper resolution maneuvers conducted by the involved aircraft. They consist of flight paths for which a penetration of any collision avoidance zone is impossible. So called “recapture maneuvers” directing an aircraft back on its scheduled track after a resolution maneuver was completed shall also be presented. Content of this article are maneuvers via horizontal turns, horizontal turns with additional vertical speed modification and via track speed modifications without horizontal direction change. Maneuvers of these kinds are generated by a geometric algorithm that analytically calculates flight path parameters on the basis of kinematic information about the involved aircraft. For the instruction of flight attitude commands to the cockpit crew, the traditional Flight Director was adapted and a novel flight guidance display was designed additionally. Both instruments were used in pilot tests on the simulator of the TU Graz “Research Platform Flight Simulation” in order to evaluate the above mentioned resolution maneuvers generated by the designed algorithm as well as the flight guidance displays. A description of these tests and their results completes this article.

1. INTRODUCTION

1.1. Statistical Data

Airborne collisions belong to the most serious accidents in aviation. In 1996, the most fatal collision occurred [Job 2006, p 42]. It happened over India, two aircraft were involved and 349 victims were the result [Ibid.]. The collision over Germany in 2002 with 71 fatalities [Bundesstelle für Flugunfalluntersuchung (BFU) 2004, pp 7] and over Brazil in 2006 with 154 fatalities [CENIPA 2008, pp 21] shall be mentioned in this context as well. Numerous incidents in which the distance between aircraft falls below a specified limit are reported every year. For the USA and on the basis of data provided by the Federal Aviation Administration (FAA), the average annual number of traffic related incidents was calculated with approximately 141 for the period between 2000 and 2010 [FAA 2011a]. For the UK and on the basis of data provided by the UK Airpox Board (UKAB), the concerning calculus resulted in 180 incidents per year for the same period [UKAB 2010, p 3; n.d.]. In Germany, the average number of reported cases between 2004 and 2010 was calculated with approximately 260 on the basis of data available from the Deutsche Flugsicherung (DFS) [DFS 2011, p 36]. Concerning data of the FAA [2011a], the UKAB [2010, p 3; n.d.] and the DFS [2011, p 36] shows an increase in the number of reported minimum distance violations in the USA, the UK and Germany from 2009 to 2010. For the USA and for Europe, an increase of air traffic is forecasted: For the USA, the FAA predicts an annual growth in the number of flights movements of 2.3% in the period between 2010 and 2030 [FAA 2011b, p 2]. EUROCONTROL predicts an increase in the number of Instrument Flight Rules (IFR) flight movements of 2.8% for Europe in the same period under the assumption of a moderate economic growth [EUROCONTROL 2010a, p 6]. An increasing number of flight movements might lead to an increasing number of traffic related incidents. The diagram in FIG. 1 indicates a relationship between IFR flight movements and the number of minimum distance violations for the period between 2004 and 2010 in Germany.

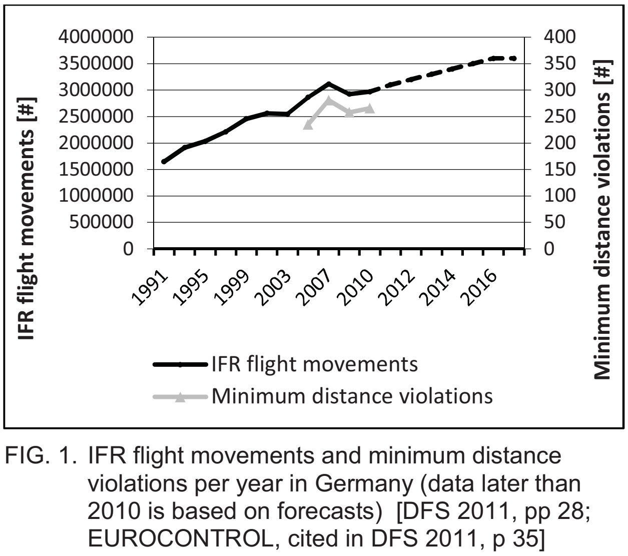

FIG. 1. IFR flight movements and minimum distance violations per year in Germany (data later than 2010 is based on forecasts) [DFS 2011, pp 28; EUROCONTROL, cited in DFS 2011, p 35]

For the resolution of air traffic conflicts, collision avoidance systems have been developed since the 1950s [Mensen 2004, p 372]. Details are provided in chapter 1.2.

1.2. Collision Avoidance Systems for Aviation

The first collision avoidance systems of the 1950s, 1960s and 1970s had insufficient communication interfaces and caused high numbers of nuisance alarms or were dependent from ground infrastructure [Ibid., p 373]. In the 1980s, the development of the Traffic Alert and Collision Avoidance System (TCAS) was initiated [Ibid.]. TCAS is a board autonomous system based on Secondary Surveillance Radar [U.S. Department of Transportation & FAA 2000, p 5]. It localizes aircraft within coverage by their transponder reply signals and calculates their approach to the own aircraft on the basis of data from these signals [Ibid., p 7]. There are two basic versions of TCAS: While TCAS I only warns cockpit crews in case of predicted, potentially dangerous approaches to the own aircraft, TCAS II furthermore calculates resolution maneuvers in the vertical plane in order to resolve traffic conflicts and avoid collisions [Ibid.]. The instruction of these maneuvers is called Resolution Advisory (RA) and is given visually and acoustically [Ibid., p 32]. For the visual instruction, specific flight guidance displays appear on the Vertical Speed Indicator and/or on the Attitude Indicator commanding the vertical speed and/or the pitch angle required for the maneuver [Ibid., p 16]. TCAS maneuvers can be conducted manually [Ibid., p 35] as well as automatically [Botargues 2008, pp 25]. For the automated conduction, Airbus presented a specific Flight Director interface (AP/FD TCAS Mode) [Ibid.].
TCAS has the following limitations:

- It exclusively calculates and instructs vertical resolution maneuvers [U.S. Department of Transportation & FAA 2000, p 5]. The scope of resolution strategies is therefore limited. This may be disadvantageous in dense traffic areas or in case the maneuverability of an aircraft involved in a conflict is limited (e.g. because the aircraft has reached its service ceiling).
- After an RA, no instructions directing the aircraft back on its scheduled track are provided by TCAS. The flight path deviation provoked by the TCAS maneuver may therefore persist longer than necessary which could lead to additional traffic conflicts with other aircraft.
- Evaluations by EUROCONTROL showed that the manual conduction of TCAS maneuvers is often imprecise (see FIG. 2).

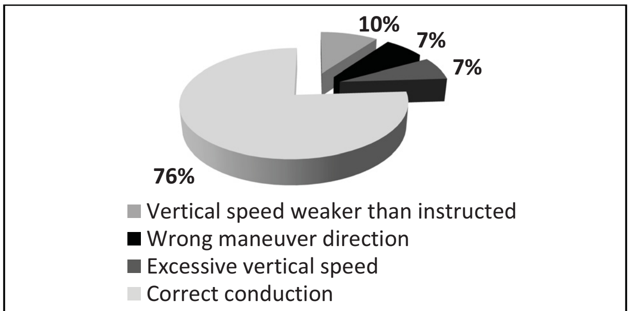

FIG. 2. Manual conduction of TCAS II RAs (basis: approx. 1000 recorded and valid TCAS II RAs in 2009) [EUROCONTROL 2010b, pp 25]

Horizontal or horizontally and vertically combined (“multidimensional”) maneuvers as alternatives to exclusively vertical maneuvers would extend the scope of traffic conflict resolution strategies. Furthermore, they could contribute to the precise conduction of resolution maneuvers due to the fact that flight path changes are provoked less sensitively by roll control inputs than by pitch control inputs [Allerton 2009, p 262].
TCAS III and TCAS IV are collision avoidance systems that calculate horizontal resolution maneuvers [Burgess, Altman & Wood 1994, pp 297]. Neither TCAS III nor TCAS IV is implemented. TCAS III is generally based on the same bearing detection principle as TCAS II [Ibid., p 298]. The bearing of a localized aircraft is thereby derived from the azimuth of the transponder reply signal transmitted by the aircraft [Ibid.]. However, the aircraft fuselage causes reflections and electromagnetic scattering of the signal which results in an insufficient bearing detection (in tests, a bearing error of up to 20° appeared) [Ibid., pp 2 98]. The conduction of horizontal resolution maneuvers exclusively based on the mentioned bearing detection method is ineffective [Ibid., p 308].
For TCAS IV, data on the position, direction and velocity etc. of an aircraft shall be based on Automatic Dependent Surveillance – Broadcast (ADS-B) and Extended Squitter (ES) [Ibid., p 309]. The ES signal format enables the transmission of a high amount of information encoded into the transponder signal (e.g. heading, 3D position, 3D velocity etc.) [Flühr 2010, p 210]. Accordingly, the bearing detection accuracy could be improved and horizontal resolution maneuvers could be enabled.

1.3. Background and Principles

Collision avoidance systems are based on algorithms for the detection and resolution of traffic conflicts (Conflict Detection & Resolution, CD&R). These algorithms evaluate flight paths with respect to possible minimum distance violations to other aircraft and calculate alternative flight paths in order to prevent these violations. CD&R algorithms could be distinguished on the basis of the following criteria:

- Time horizon for the calculus and instruction of resolution maneuvers (state based algorithms project the current position of an aircraft on the basis of its current velocity, intent based algorithms include e.g. Flight Management System waypoints into their calculus in order to guarantee a wider time horizon [Kuchar & Yang 1997, p 1389]).
- Consideration or negligence of aircraft dynamics (e.g. turn radius) in the calculus.
- Dimensions of the calculated resolution maneuvers (vertical, horizontal or multidimensional).
- Consideration or negligence of recapture maneuvers in the calculus.
- Mathematical solution strategy for calculating maneuver flight path parameters (analytical, numerical).
- Maximum number of aircraft simultaneously involved in a traffic conflict that can be considered by the algorithm.
- Number of aircraft conducting a resolution maneuver in a traffic conflict.

Chapter 1.3.1 and 1.3.2 describe some details of specific CD&R algorithms in order to prepare the principles this article is based on.

1.3.1. TCAS II Algorithm

For the detection of traffic conflicts, TCAS generally conducts two tests: The range test evaluates after which period of time a specified minimum distance threshold between the own aircraft and localized aircraft will be violated according to a state based prediction [U.S. Department of Transportation & FAA 2000, pp 22]. The altitude test determines after which period of time the involved aircraft reach co-altitude [Ibid., p 22]. The tests are based on position information derived from the transponder reply signals of localized aircraft [Ibid., pp 17]. Approach speeds required for the calculus are numerically derived from the position information [Ibid., p 26].
If both range and altitude test result in time values falling below a specified threshold, a vertical resolution maneuver is calculated [Ibid., p 22]. Thereby specified vertical speed values are evaluated with respect their capability of resulting in sufficient relative vertical distance between the involved aircraft at their closest point of approach [Ibid., p 28]. The least disruptive vertical speed is selected and instructed [Ibid.].
A TCAS resolution maneuver is instructed via an RA (see chapter 1.2). An RA is canceled as soon as the distance between the involved aircraft is increasing again [Ibid., p 30]. Recapture maneuvers are not part of TCAS II.

1.3.2. Algorithms for the Calculus of Horizontal and Multidimensional Maneuvers

A large number of algorithms that are capable of calculating horizontal or multidimensional resolution maneuvers beside vertical maneuvers can be found in the literature.
However, there are aspects or combinations of aspects which have not been considered yet.
Carbone et al. [2006, pp 1580] describe a state based algorithm for the resolution of traffic conflicts in the horizontal or vertical plane. The algorithm uses an analytical solution strategy which is based on the solution of 4^{th} order polynomial functions [Ibid.]. An a priori consideration of curved flight paths and track accelerations is not included [Ibid.]. Multidimensional maneuvers are not reflected. The ansatz of Goss, Rajvanshi and Subbarao [n.d., pp 1] deals with horizontal, vertical and multidimensional resolution maneuvers and allows analytical solutions for the calculated flight path parameters in specific cases [Ibid.]. For the solution of general cases, methods of numerical optimization are presented [Ibid.]. The dynamics of aircraft are not considered [Ibid.].
Paielli [2003, pp 407] presents an algorithm that considers the dynamics of aircraft. The solution finding process is numerical and multidimensional maneuvers are not considered [Ibid.].
In the next chapter, the designed algorithm is described on the basis of the explanations provided above.

2. THE DESIGNED CD&R ALGORITHM

The CD&R algorithm presented in this article has the following basic characteristics:

- The algorithm is state based and projects the current state of motion of involved aircraft in order to detect possible traffic conflicts.
- The dynamics of aircraft are considered. The CD&R algorithm provides an approximate model of curved trajectories derived from their geometries.
- The calculation of resolution maneuvers is the result of the aircraft state of motion projection and detection of traffic conflicts.
- The algorithm calculates resolution maneuvers consisting of horizontal turns and horizontal turns which are complemented by vertical speed modifications. Maneuvers consisting of exclusive track speed modifications are possible as well. The calculated maneuvers have the following characteristics:
    - The calculated lead time before the start of a resolution maneuver is as large as possible in order to fulfill the basic requirement for a collision avoidance system of acting as last “safety-net” after all previous measures of establishing appropriate separation between aircraft were unsuccessful.
    - The flight path deviation caused by the resolution maneuver is kept as small as possible (with respect to the calculated lead time).
    - The transitions from less curved flight path segments to more curved segments and vice versa are modeled as clothoids. For the reason of simplicity, a description of this detail will not be given here.
- Recapture maneuvers are included.
- The solution strategy for the used mathematical equations is analytical.
- The algorithm is capable of resolving conflicts between two or more aircraft. For the reason of brevity, the description of the traffic conflict resolution process shall be focused on conflicts with two aircraft.

In the following text, basic functions of the presented algorithm shall be described on the basis of traffic conflicts involving two aircraft. Thereby, the following, simplifying prerequisites shall be used[1]:

1) During the entire process (before and after a resolution maneuver), the aircraft do not change their altitude.
2) Only one aircraft conducts a resolution maneuver. The other aircraft does not change its track.
3) Before the resolution maneuver starts, the flight path of the aircraft that conducts a resolution maneuver is straight and the aircraft has constant velocity.
4) During the entire process, the flight path of the aircraft not conducting a resolution maneuver is straight and the aircraft has constant velocity.
5) Aircraft will be considered as points in the calculus. The aircraft symbols displayed in the figures below are used for a better visualization of traffic conflicts only.

The following abbreviations are used in explanations and figures below:

OS: Own Ship (own aircraft)
TG: Target (aircraft involved in the traffic conflict together with OS)

[1] Special cases in which specific prerequisites are not met are properly marked.

Z: Cylindrical collision avoidance zone around TG
I: First point in time considered in the figures
II: Second point in time considered in the figures
v_{OS}: Current velocity of OS
v_{TG}: Current velocity of TG
d_0: Distance between OS and TG at point in time I
t_V: Lead time before the resolution maneuver starts
k: Resolution maneuver flight path
k‘: Recapture maneuver flight path
r_Z: Radius of Z
ε: Angular position of OS with respect to TG at point in time II
s: Straight line segment approximating a curved trajectory
α: Direction of s with respect to the x-axis of the given coordinate frame
t_s: Total time of OS on a straight line segment
a: Acceleration of OS
t_a: Duration of the acceleration phase
v_{OSc}: Constant speed after the acceleration phase

FIG. 3 shows the cylindrical collision avoidance zone around TG in detail.

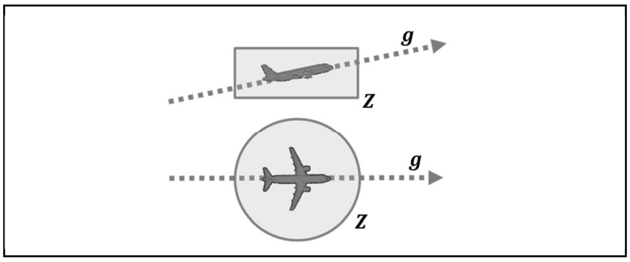

FIG. 3. Horizontal and vertical perspective of Z around TG. Flight path g of TG.

FIG. 4 shows OS being situated partially inside Z of TG at point in time II.

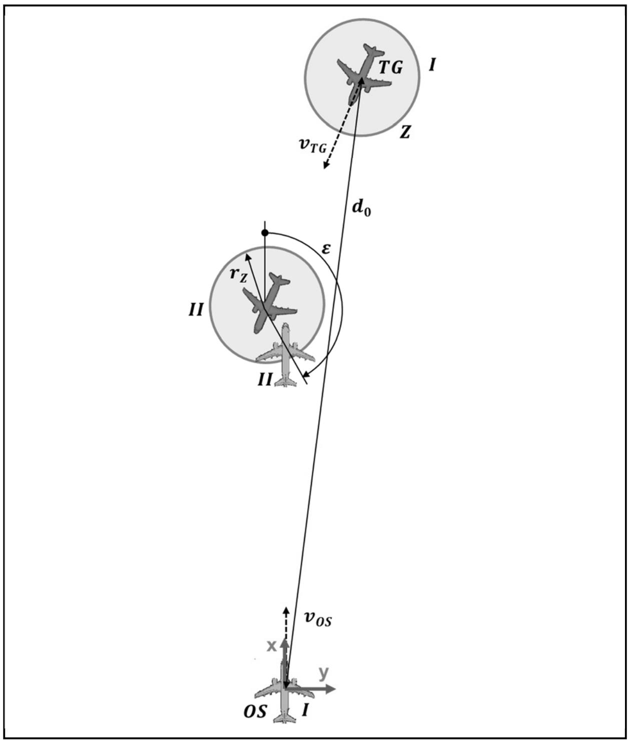

FIG. 4. Traffic conflict

Every mathematical expression shown below is expressed with respect to the cartesian coordinate frame displayed in e.g. FIG. 4. The coordinate frame is placed in OS and moving with OS.
The following expressions describe the situation of OS being situated on the perimeter of Z:

$$(1)\quad \begin{bmatrix} v_{OS}\, t \\ 0 \end{bmatrix} - \begin{bmatrix} d_{0x} \\ d_{0y} \end{bmatrix} - \begin{bmatrix} v_{TGx}\, t \\ v_{TGy}\, t \end{bmatrix} = \begin{bmatrix} r_Z \cos(\varepsilon) \\ r_Z \sin(\varepsilon) \end{bmatrix}$$

Squaring the x- and the y-component of (1) and adding the results give a quadratic equation for t. This quadratic equation would have to be solved for the time t which reflects a situation in which OS is situated on the perimeter of Z. A penetration of the collision zone will occur “in the future” if at both solutions are positive which indicates a traffic conflict.
In FIG. 5, the traffic conflict shown in FIG. 4 and described by (1) is resolved by a maneuver of OS which conducts a right turn shown by the path k. A recapture maneuver is also displayed in FIG. 5 consisting of a left turn (path k’) and directing OS back on its scheduled track.

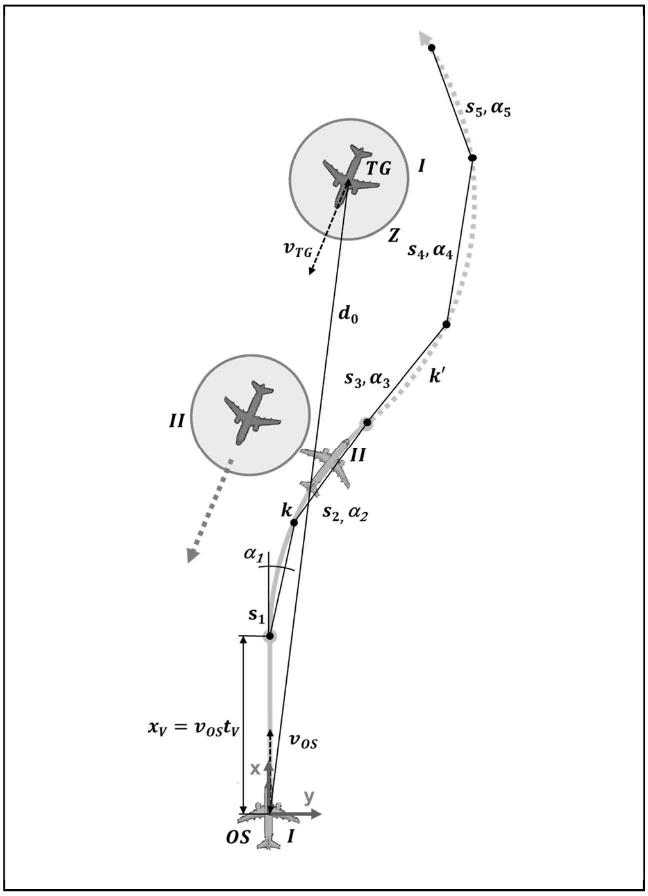

FIG. 5. Right turn traffic conflict resolution maneuver

The curved trajectory k in FIG. 5 is approximated by two straight line segments s_1 and s_2 with given lengths and directions[2]. For each line segment, a specific calculus has to be performed. The basis of this calculus is given by the situation of OS being situated on the perimeter of Z after a

[2] It is also possible to model k on the basis of more than two line segments. This is not described here.

time $t_V+t_{s1}+t$ or t_V+t respectively. The following expressions describe this situation for s_2 and s_1.

$$\begin{bmatrix} v_{OS}\, t_V \\ 0 \end{bmatrix} + \begin{bmatrix} v_{OS}\, t_{s1}\cos(\alpha_1) \\ v_{OS}\, t_{s1}\, sin(\alpha_1)\end{bmatrix} + \begin{bmatrix} v_{OS}\, t\cos(\alpha_2) \\ v_{OS}\, t\, sin(\alpha_2)\end{bmatrix} - \begin{bmatrix} d_{0x}\\ d_{0y}\end{bmatrix} - \begin{bmatrix} v_{TGx}\,(t_V+t_{s1}+t) \\ v_{TGy}\,(t_V+t_{s1}+t)\end{bmatrix} = \begin{bmatrix} r_Z\cos(\varepsilon) \\ r_Z \sin(\varepsilon)\end{bmatrix} \quad (2)$$

$$\begin{bmatrix} v_{OS}\, t_V \\ 0 \end{bmatrix} + \begin{bmatrix} v_{OS}\, t\cos(\alpha_1) \\ v_{OS}\, t\, sin(\alpha_1)\end{bmatrix} - \begin{bmatrix} d_{0x}\\ d_{0y}\end{bmatrix} - \begin{bmatrix} v_{TGx}\,(t_V+t) \\ v_{TGy}\,(t_V+t)\end{bmatrix} = \begin{bmatrix} r_Z\cos(\varepsilon) \\ r_Z \sin(\varepsilon)\end{bmatrix} \quad (3)$$

Squaring the x- and y-component of (2) and adding the results give a quadratic equation which can be solved for t (the same procedure is conducted for (3)). In the solution for t_{1_2}, t_V appears with highest order two. Therefore, t_V can be determined easily in a way that there is no solution for t that would reflect a future point in time on s_2. This together with the situation that there is no real number solution for t are the preferable case because it means that OS flying along the segment does not intersect Z at a future point in time. By inserting preferable solutions for t_V in the quadratic equation resulting from the manipulations on (3) described above and adapting t_V if necessary, a conclusive solution for t_V can be found that reflects the situation of both line segment not intersecting Z in the future.

For the determination of the recapture maneuver a similar method as for the detection of traffic conflicts is used. k‘ is modeled by straight segments (e.g. by s_3, s_4 and s_5), every segment is evaluated with respect to its potential of penetrating Z. This is done cyclically during OS is moving along k. As soon as the calculus shows that a penetration of Z is not possible for any segment, the recapture maneuver is instructed.

The designed algorithm allows the combination of a horizontal turn with a vertical speed modification (prerequisite 1) is invalid in this case). In this case, a fixed setpoint vertical speed is instructed in order to complement the horizontal maneuver and additionally extend the distance at the closest point of approach between OS and TG.

The resolution of the traffic conflict displayed in FIG. 4 may be achieved by an exclusive track speed modification of OS (without a heading change). Therefore, the t_V required for the conflict resolution is calculated under the prerequisite of a flight phase of constant acceleration in order to achieve a defined setpoint speed v_{OSc} which is then kept constant for a time t. The basis of the conflict resolution via sole track speed modification is a situation in which OS is situated on the perimeter of Z after a time t_V+t_a+t. The following expression describes this situation:

$$\begin{bmatrix} v_{OS}\, t_V \\ 0 \end{bmatrix} + \begin{bmatrix} v_{OS}\ \ t_a + a\,\dfrac{t_a^{\,2}}{2} \\ 0 \end{bmatrix} + \begin{bmatrix} v_{OSc}\, t \\ 0 \end{bmatrix} - \begin{bmatrix} d_{0x}\\ d_{0y}\end{bmatrix} - \begin{bmatrix} v_{TGx}\,(t_V+t_a+t) \\ v_{TGy}\,(t_V+t_a+t)\end{bmatrix} = \begin{bmatrix} r_Z\cos(\varepsilon) \\ r_Z \sin(\varepsilon)\end{bmatrix} \quad (4)$$

The solution process is generally identical to the conflict resolution via right turn. The x- and the y-component in (4) are squared and the results are added which gives a quadratic equation that can be solved for t. t_V is selected in a way that no solution exists that would reflect a future point in time on the trajectory of OS. FIG. 6 shows the resolution of a traffic conflict via track speed modification.

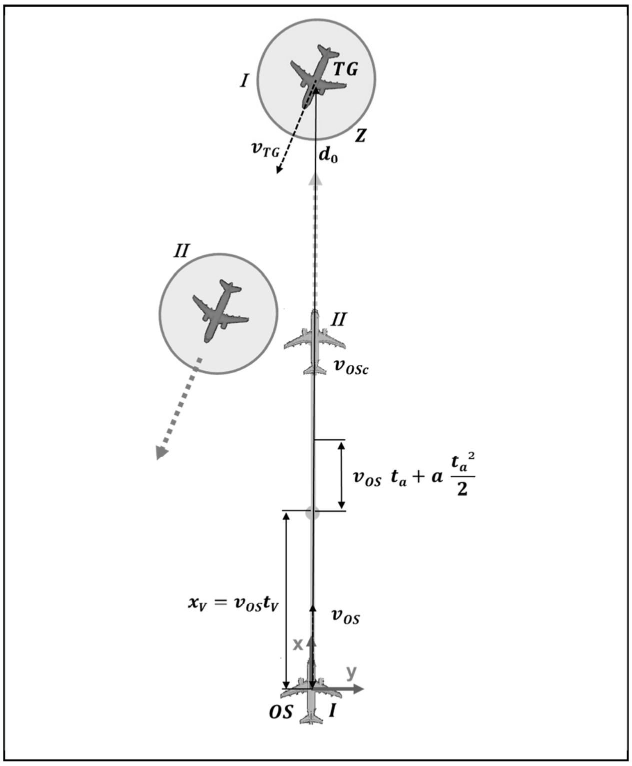

FIG. 6. Conflict resolution via exclusive track speed modification

For resolution maneuvers consisting of horizontal curves and horizontal curves combined with vertical speed modifications, flight attitude commands are generated by PID controllers[3].

The calculated resolution maneuver flight path and the concerning flight attitude commands are updated in defined time intervals in order to reflect the current motion states of OS and TG. The calculated attitude commands show on flight guidance displays. This aspect is described in chapter 3.

3. INSTRUCTION OF RESOLUTION MANEUVERS

In case of the manual conduction of a TCAS II maneuver, required vertical speeds and/or flight attitudes are instructed via specific flight guidance displays. For EFIS (Electronic Flight Instrument System) applications, these displays appear on the Vertical Speed and/or Attitude Indicator of the Primary Flight Display (PFD) [U.S. Department of Transportation & FAA 2000, p 16]. FIG. 7 shows a PFD with the concerning flight guidance display for the instruction of a TCAS maneuver. On the Navigation Display in FIG. 7, a symbol [1] shows at the proper relative position to the own aircraft [Ibid., pp 15]. This indicates an aircraft which causes a TCAS RA [Ibid.]. The trapezoid line cue [2] in the Attitude Indicator indicates the pitch

[3] The determination and the instruction of air speed commands for resolution maneuvers via track speed modification have not been implemented yet.

angle required for the conduction of the RA [Ibid., p 14]. The pitch angle has to be kept outside [2] during the RA [Ibid. p 35]. The vertical speed has to be kept inside the area [3] that shows in the Vertical Speed Indicator [Ibid.]. The areas inside [2] and [4] have to be avoided during the maneuver [Ibid., p 16].

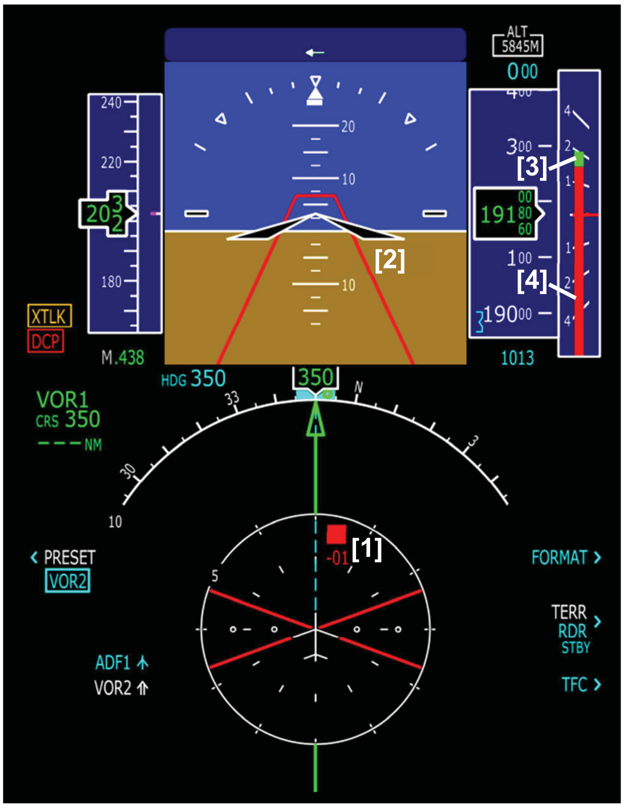

FIG. 7. TCAS II maneuver guidance displays

TCAS II is implemented in the simulator of the TU Graz Research Platform Flight Simulation.

The presented CD&R algorithm is part of the so called "Extended Collision Avoidance System" (XCAS) which was designed together with the algorithm and is also implemented in the simulation environment of the research platform. For the instruction of XCAS resolution maneuvers, a Flight Director symbol (V-Bar) was adapted (magenta/black hatched coloring indicating computer generated flight paths etc.). Additionally, the so called "Alternative Display" (ADIS) was designed. For the automated conduction of resolution maneuvers, XCAS is connected to the autopilot of the simulator[4].

FIG. 8. XCAS FDS

FIG. 8 shows a PFD with the "XCAS Flight Director Symbol" (FDS) during the instruction of a resolution maneuver.

The own aircraft wing symbol [1] of the attitude indicator in FIG. 8 has to match the FDS [2] during the maneuver. This state is displayed in FIG. 8. The display [3] in the autopilot Mode Annunciator Panel indicates that the aircraft is laterally guided by XCAS. The display [4] indicates vertical guidance by XCAS as the maneuver shown in FIG. 8 is multidimensional.

FIG. 9 shows a PFD with the XCAS ADIS during the instruction of a resolution maneuver.

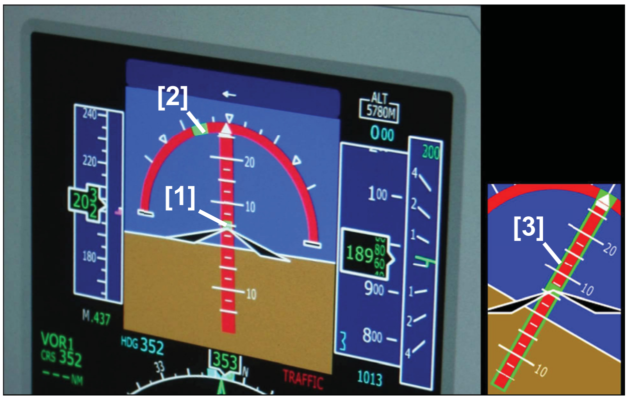

FIG. 9. XCAS ADIS und AFF

The pitch- and roll angle commands of an XCAS maneuver appear as green areas in front of a red background ([1]: pitch angle instruction, [2]: roll angle instruction). In case the instructed attitude is kept, a green frame [3] appears giving feedback to the cockpit crew. This frame is therefore called "Attitude Feedback Frame" (AFF).

A difference between FDS and ADIS is the fact that the roll angle instruction of the FDS is continuous while for the ADIS it is not: Area [2] in FIG. 9 would for instance "jump" from 0° to 20° roll.

The XCAS display of traffic aircraft on the Navigation Display is exactly the same as for TCAS II (see FIG. 7).

In order to evaluate the flight path geometries and flight attitudes generated by the designed CD&R algorithm as well as automatically conducted XCAS maneuvers, pilot tests on the simulator of the research platform were

[4] The autopilot system of the system shall not be described here.

carried out. The following chapters describe the research simulator as evaluation environment for the pilot tests, the test procedure as well as some test results.

4. PILOT TESTS: EVALUATION ENVIRONMENT AND TEST PROCEDURE

The TU Graz research simulator is a fixed base simulator with a generic flight dynamics model adapted to the characteristics of airliners. The cockpit had been part of a Mc Donnell Douglas DC10 simulator before it was purchased by the TU Graz. Its analogous instruments were replaced by a modern EFIS. Primary controls (control column, thrust levers etc.) are still original. The spherical vision dome has an aperture angle of approximately 200° and the terrain display is generated by 3 LCD projectors. Re-synthesized real aircraft voice recordings are the basis of the sound system. The following list shows important systems of the simulator[5]:

- EFIS: Rockwell Collins ProLine21
- Enhanced Ground Proximity Warning System (EGPWS): Honeywell MKVIII
- TCAS II: Rockwell Collins TCAS-4000
- XCAS (experimental)
- Flight Management System (FMS): Universal UNS-1
- Moving Map: Becker MFD6203

FIG. 10 shows the cockpit of the research simulator.

FIG. 10. The simulator cockpit of the TU Graz Research Platform Flight Simulation

The software design of the simulator is modular. Basic component is the Kernel FGED (FlightGearEngineDynamics) which simulates the flight dynamics, the gear and the engines of the simulator. Additionally, other components exist, e.g. EFIS, Atmosphere, Controls, Visual System etc. TCAS II and XCAS also form separate components of the simulation environment. The communication between the components is handled via UDP datagrams which are transmitted into the simulator network and received from there via an Ethernet interface. FIG. 11 shows parts of the simulator network topology.

[5] Apart from XCAS, all systems are replicas of products of the mentioned manufacturers.

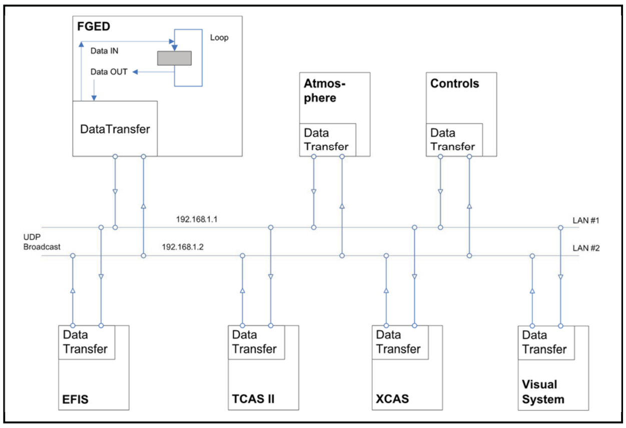

FIG. 11. Parts of the simulator network topology

The following aspects formed the content of the pilot tests which were conducted in cooperation with the University of Graz, Institute of Psychology:

- Comparison of TCAS II und XCAS
- Comparison of different maneuver flight path geometry types generated by the designed algorithm.
- Comparison of FDS and ADIS
- Comparison of manually and automatically conducted XCAS resolution maneuvers

The comparisons were based on technical points of view as well as on human factors. They were conducted in the context of test flights with 32 pilots (more than 80% were commercial pilots and ATPL holders respectively). During the tests, flight data was recorded in order to gain insight into the precision maneuvers were manually conducted with. The following pieces of flight data were collected:

- Relative position between the own aircraft and the other aircraft involved in the conflict (the so called “target” aircraft)
- Velocity
- Flight attitude
- Various system state indicators

Psycho-physiological data (heart rate via electrocardiogram etc.) was additionally collected during the tests in order to estimate aspects like the extent of workload or stress during the resolution of a traffic conflict. Each test person had to resolve a specific number of simulated traffic conflicts in her/his test flight. The traffic conflicts had the following characteristics:

- Two aircraft involved, only the own aircraft had to maneuver in a conflict.
- Distance between own aircraft and target aircraft at the start of the conflict simulation: 15NM
- Bearing of target aircraft at the start of the conflict simulation: 15°
- Distance between own aircraft and target aircraft at their closest point of approach: 0,236NM
- Bearing of target aircraft at the closest point of approach: 286°
- Relative vertical position of target aircraft with respect to own aircraft: 70ft below
- Time from the start of the conflict simulation to the closest point of approach: 90s

The traffic conflict resolution was alternately assisted by TCAS II and XCAS. For TCAS, the flight guidance displays shown in FIG. 7 were used. For XCAS, the resolution maneuvers were alternately instructed by FDS and ADIS (see FIG. 8 and FIG. 9). For both, FDS and ADIS, different flight path geometry types generated by the presented algorithm were evaluated:

- Horizontal (“H”)
- Combined Horizontal and Vertical (“CHV”)
- Separated Horizontal and Vertical (“SHV”)

FIG. 12, FIG. 13 and FIG. 14 show the different geometry types in detail.

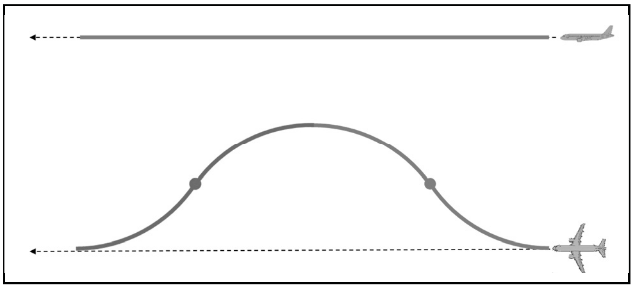

FIG. 12. Maneuver geometry H

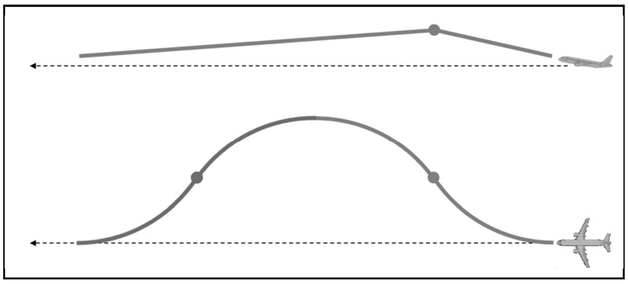

FIG. 13. Maneuver geometry CHV

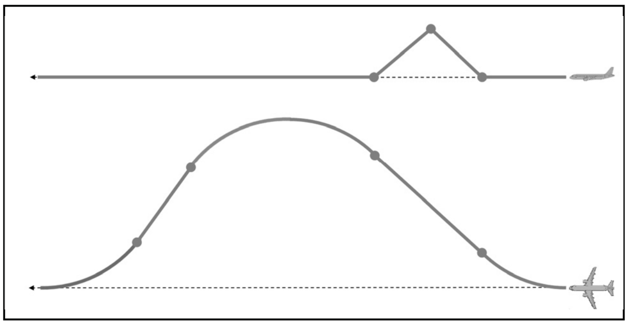

FIG. 14. Maneuver geometry SHV

Resolution maneuvers instructed by the FDS had to be conducted manually as well as automatically by the test persons. All other maneuvers were conducted manually. Chapter 5 shows some results from the pilot tests.

5. PILOT TESTS: RESULTS

The difference between the pitch angle instructed by the collision avoidance system and the actual pitch angle of the aircraft is important to gain insight into the precision a resolution maneuver is manually conducted with. Accordingly, a comparison between TCAS II and XCAS was conducted on the basis of this parameter. Therefore, it appears in FIG. 15 to FIG. 17.

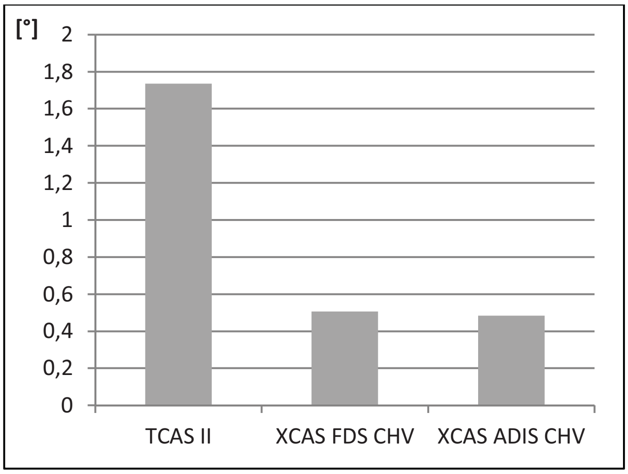

FIG. 15. Difference between instructed pitch angle and actually flown pitch angle (average over the complete maneuver time and all test persons)

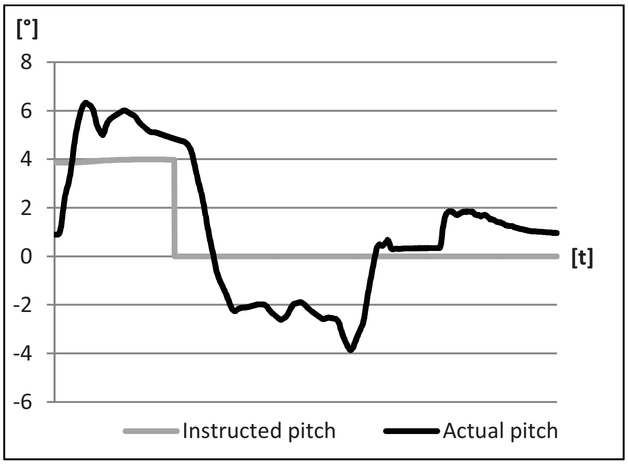

FIG. 16. Difference between instructed pitch angle and actually flown pitch angle for a TCAS II maneuver (example pilot behavior during the entire maneuver)

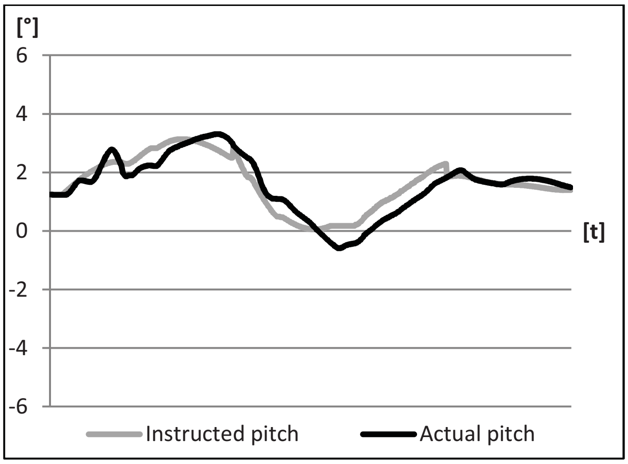

FIG. 17. Difference between instructed pitch angle and actually flown pitch angle for an XCAS CHV maneuver (example pilot behavior during the entire maneuver)

The heart rate is a parameter that gives insight into the extent of human emotions, habituation, stress etc.

[Gramann & Schandry 2009, p 95]. Results of the conducted heart rate measurements shall be presented here. FIG. 18, FIG. 19 and FIG. 20 show results for different scenarios in diagram format.

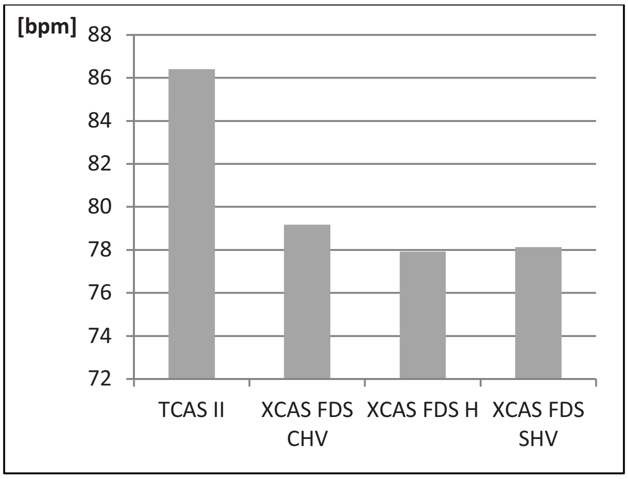

FIG. 18. Heart rate in beats per minute (bpm): comparison of TCAS II and XCAS with FDS (average over the first 10s of the resolution maneuver and all test persons)

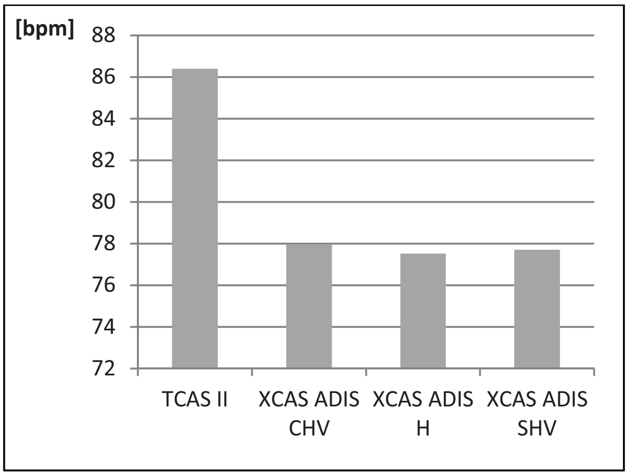

FIG. 19. Heart rate: comparison of TCAS II and XCAS with ADIS (average over the first 10s of the resolution maneuver and all test persons)

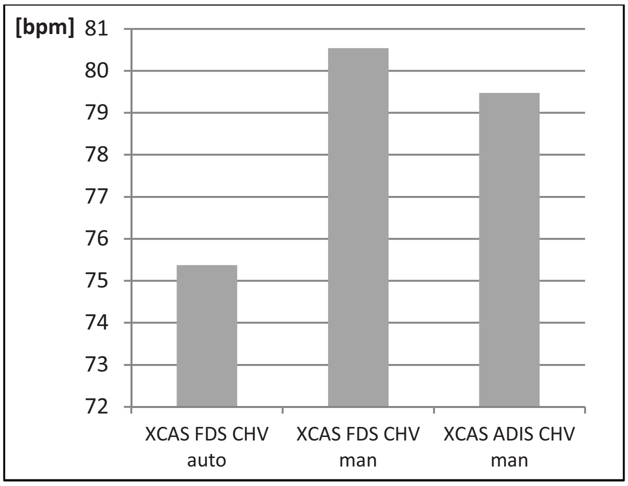

FIG. 20. Heart rate: comparison of manual and automated XCAS maneuver conduction (average over the first 10s of the resolution maneuver and all test persons)

Chapter 6 shows an interpretation of the results.

6. DISCUSSION AND OUTLOOK

A novel, geometric CD&R algorithm was presented which shows differences to the developments described in [5], [13] and [18]. The capability of considering aircraft dynamics without the need of using numeric solution strategies for the calculus of maneuver flight path parameters shall be mentioned in particular.

TCAS II is the only collision avoidance system in service that calculates and instructs resolution maneuvers in order to resolve air traffic conflicts. However, in contrast to the presented design, TCAS II provides maneuvers in the vertical plane only.

Furthermore, the XCAS flight guidance displays FDS and ADIS were described which form interfaces between the presented algorithm and the pilot. Via these interfaces, the flight paths generated by the algorithm and the interfaces themselves were evaluated. The results of this evaluation were interpreted as follows:

- The average precision in achieving and keeping an instructed pitch angle is for both FDS and ADIS significantly higher than for the TCAS II guidance displays (FIG. 15 to FIG. 17).
- The average heart rate for the manual conduction of an XCAS resolution maneuver is for both FDS and ADIS as well as for all maneuver geometry types significantly lower than for the TCAS II guidance displays in the considered time interval (see FIG. 18 and FIG. 19). This may indicate a lower average extent of stress, emotions etc. for XCAS maneuvers and XCAS guidance displays.
- In the considered time interval, the average heart rate for the automated conduction of XCAS CHV maneuvers is significantly lower than for the manual conduction (this applies for both FDS and ADIS) (see FIG. 20). This may indicate a lower average extent of stress, emotions etc. for the automated conduction of resolution maneuvers.

The results indicate that the resolution maneuver flight paths generated by the described algorithm are feasible with respect to technical as well as psycho-physiological points of view. Further evaluations will comprise the treatment of traffic conflicts with more than two aircraft involved and the resolution of traffic conflicts by sole track speed modifications.

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