VOD-CA - Assisting Human Flight Performance and Situation Awareness in Lateral Deconflicting

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Abstract

Velocity-obstacle based collision avoidance displays can provide the pilot with information about potential conflicts and assist manual avoidance manoeuvres. Lateral deconflicting assistance is a significant field in aviation research since it complements vertical conflict resolution provided by available collision avoidance systems (ACAS/TCAS). Avoiding conflicts in the horizontal plane increases the number of options for a more efficient deconfliction. VOD-CA (Velocity-Obstacle based Display for Collision Avoidance) is a display implementation developed by DLR to enhance pilot awareness of potential conflicts in velocity space and provide necessary information to derive lateral conflict resolving manoeuvres (Peinecke et al., 2013). It represents conflict geometries in a track-up velocity space, centred on own-ship speed and heading. In a first explorative study participants with flight simulation experience flew several scenarios using VOD-CA to avoid conflicts, while their situation awareness was assessed. The results indicate adequate situation awareness. Participants could stay sufficiently separated from other aircraft by choosing safe headings and speeds. It is discussed that some aspects of the display could be misinterpreted when confused with spatial hints. Nevertheless essential information could be derived to stay clear of potential conflicts.

Intoduction

Background

Midair collisions are still a serious safety threat in aviation today. Several layers of protection are in effect, which were established in history of aviation to keep aircraft safely separated during flight. The pilot of an aircraft is still required to maintain situation awareness, to observe the surrounding traffic at all times, obey right-of-way rules and take the necessary measures to avoid conflicts and prevent collisions. In standard cruise flight aircraft must stay separated several miles laterally and at least 2000 feet (1000 feet in reduced vertical separation minima RVSM) vertically. Air traffic control ensures these limits in Instrument Flight Rules (IFR) operations. Still, representing only one safety layer, IFR-separation may fail, which is why additional technological safety layers have been introduced, and the pilot is still required to observe surrounding traffic ("See and Avoid", Federal Aviation

In D. de Waard, K. Brookhuis, R. Wiczorek, F. di Nocera, R. Brouwer, P. Barham, C. Weikert, A. Kluge, W. Gerbino, & A. Toffetti (Eds.) (2014). Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2013 Annual Conference. ISSN 2333-4959 (online). Available from http://hfes-europe.org

Administration, 1983), even when not flying under Visual Flight Rules (VFR). The display technology assessed in this work aims to support situation awareness for a human pilot, whether flying under IFR or VFR, in terms of recognizing conflicting traffic and, if separation loss is imminent, having adequate information to steer clear of a conflict.

In this paper a new display concept for self-separation and deconfliction is introduced. Also a study is presented in which the display's comprehensibility and pilots' situation awareness were tested.

Collision avoidance and self-separation

Separation of aircraft is a safety layer in aviation to keep aircraft far enough apart to leave time for controllers and pilots to communicate, assess and plan the situation. Cases of separation losses are called conflicts in the scope of this work. The risk of a collision is imminent, whichever protection layer, that was in place to ensure separation, failed. The pilot of an aircraft is required by law to observe the surrounding traffic at all times, obey right-of-way rules and take the necessary measures to avoid conflicts and prevent mid-air collisions. This principle is known as the See and Avoid-rule in manned aviation (Federal Aviation Administration, 1983). Without the assistance of technological devices and support functions, the pilot has to watch surrounding traffic with the naked eye. There are limits to See and Avoid however, given by the atmospheric conditions and human perception limits, e.g., the resolution of the human eye, attention span, alertness and the ability to create a mental representation of the current traffic scenario. Many incidents took place, even in the best of conceivable viewing conditions (Hobbs, 1991).

Many ways were sought to assure aviation safety even in adverse conditions, including but not limited to operational measures, procedures and air navigation services. Technical assistance functions were invented to alert the pilot in case that all other safety layers are failing and an imminent collision requires immediate action.

The invention of the Airborne Collision Avoidance System (ACAS) and the introduction of the Traffic Alert and Collision Avoidance System (TCAS; as a concrete implementation) in the 80s of the last century posed a milestone in airborne collision avoidance systems. With all aircraft TCAS-equipped, it became possible to collect information on aircraft nearby, even without visual confirmation. Furthermore, through its sophisticated logic, TCAS is not only alerting involved airspace users of an imminent conflict, it also resolves the conflict by negotiating the respective manoeuvres aboard both aircraft. Thus, the pilot is informed about close traffic with traffic advisories (TA) and in situations where action has to be taken to resolve the conflict, pre-calculated (and automatically negotiated) resolution advisories (RA) are issued. TCAS contributed dramatically to a very high level of aviation safety since its introduction and it prevented many collisions where other safety layers failed. However, TCAS resolves conflicts only vertically, and it has a significant bearing error in localizing other aircraft (e.g. Law, 2005). Furthermore, TCAS is a last layer safety net, and never was intended to assist situation awareness. It was designed to inform the pilot and tell him how to resolve a dangerous situation.

It decides about collision avoidance manoeuvres without keeping the human, neither air traffic control operator, nor the pilot, in the loop. In cases where pilots tried to extend their involvement in conflict resolution based on TCAS, dangerous situations were produced (Law, 2005). Although it is technically possible for the pilot today to see surrounding traffic on a TCAS-display the information provided is coarse, and reflects only the current positions of all surrounding aircraft. Moreover, the display may be mistaken for a radar display, which shows dynamic events in front of a static background. The user might suspect, that he observes the absolute movement of an intruding airplane, where he in fact sees only relative movement. This is due to the fact, that the display is centred on the own ship position, which is not static while in flight. In (Law, 2005), a situation is described, where the pilot had the impression, the traffic was steering directly into him, and the controller was about to direct him right into the traffic, where in fact both airplanes were flying almost orthogonally and the controller chose the right manoeuvre to steer immediately clear of conflict. Lessons learned from this event were operational adjustments and the procedural instruction that "the TCAS traffic display must not be used for self-separation" (Law, p. 4).

Still, the possible benefit of additional information to assist the correct prediction of the outcome of a conflict remains. In remote oceanic flight for example, TCAS is carefully used to allow for more effective climb manoeuvres, adding local TCAS information to the rather vague positional information air navigation services can provide from the distance. Displays that visualise traffic positions on a moving map are not adequate for self-separation, but even dangerous. But other ways of visualization may well prove beneficial for situation awareness and conflict avoidance. For example, displays showing conflicting velocities of other aircraft with the own ship velocity could assist the pilot to foresee a separation loss as well as an imminent collision and help to avoid it early. Such a display could add significantly to aviation safety and efficiency at the same time, e.g., by showing horizontal conflict solutions. Early information about a future conflict in cruise flight would allow for slight adjustments of the speed or heading, which is referred to as lateral deconflicting, to stay safely separated and clear of conflict without leaving the flight level.

Velocity-obstacle based displays are developed to provide such information in a different visualization concept. Velocity obstacles are a representation of velocities within a velocity space and thus can represent a conflict (detailed description below). The concept of velocity obstacles (VO) is known for several decades and was extensively researched in robotics, path-planning, collision free movement (see Peinecke et al., 2013). However, in recent years, its possible application in traffic and aviation scenarios has come into scope. In recent years, velocity space based display prototypes have been proposed, e.g., display studies concerning lateral deconflicting were presented by Technical University Delft (NL) showing velocity obstacles in a spatial navigation context (e.g. Van Dam, Mulder, & Van Paassen, 2007). However, the Delft displays overlay spatial position information with the velocity space, which may bear a risk of confusing both information and misinterpretation, a problem that lead to the banning of TCAS for self-separation. The pilot should not be easily allowed to confuse the indication of own ship position with a very different indication of own ship velocity in a completely different space. Furthermore a velocity obstacle could be mistaken for a spatial obstacle and lead to an impulse to outmanoeuvre it, e.g., flying around the assumed dangerous area whereas adjusting the velocity would have been correct. The VOD-CA display assessed in this work was designed as a stand-alone additional system and not as a feature of existing displays. It strictly does not contain any spatial position reference to overcome the danger of misinterpretation.

VOD-CA

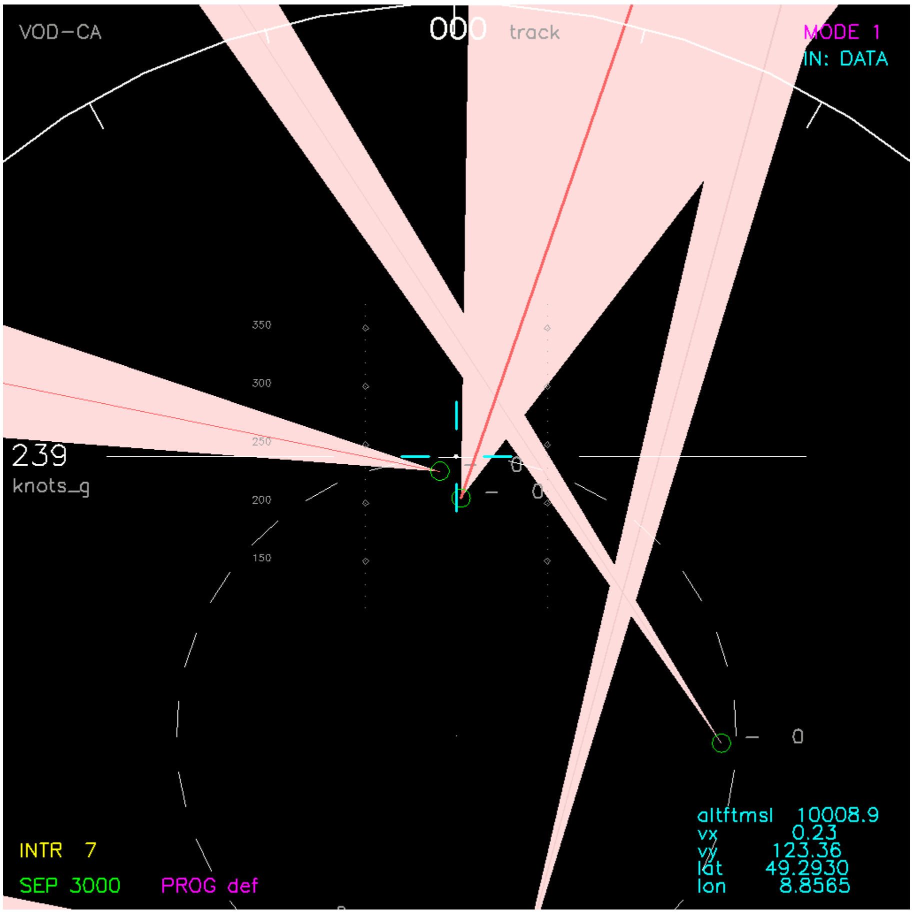

Figure 1. Velocity-Obstacle based Display for Collision Avoidance (VOD-CA)

The VOD-CA display implementation for collision avoidance has a strong focus on velocity space visualization. The main part of the display depicts the velocity space as seen from above. Velocity obstacles are drawn into that space. The y-axis of the display relates to the forward speed (“track”), the x-axis to speeds orthogonal to the current movement direction. Since the display is designed to assist pilots in their awareness and assessment of the current and future situation, the velocity space is always rotated such that its y-speed is aligned with the own-ship movement, similar to a track-up display for navigation. Furthermore, the velocity space is continuously centred on the own ship speed.

The display shows track (course over ground) and speed information similar to the established appearance in the common flight displays (see Figure 1). Acceleration of the own ship by thrust input shifts the velocity space up and down while a direction change rotates the display. Note, that there is no spatial reference to the own ship position in this display. The cross-hair always remains in the middle of the display. The velocity obstacles (VOs) are drawn into the space as triangular shapes marking areas of speed and heading that lead to future conflicts if the dot which marks own ship velocity remains within one of these areas. The tip of a VO marks an intruder aircraft's velocity, i.e., from the distance of the cross-hair to the pointy ends of the VOs, the relative velocity can be assessed. As the VO edges are the tangents to the other aircraft's separation zone the VO of nearer planes have a broader angle than those of distant aircraft. Again, this is only indirectly conveying information of the intruder aircraft positions.

The nature of a velocity space implies that it features speeds and directions of movement, not spatial relationships. They are of course implicitly contained, as much as relative movement is implicitly conveyed by a spatial display updating in time. Both paradigms however allow for immediate understanding of one of these aspects and a more trying determination of the other. VOD-CA explicitly is designed to provide a velocity space representation to see conflicting speeds instantaneously and is not meant to replace existing spatial displays.

Research question

It is assumed that pilots can use VOD-CA to stay safely separated from other aircraft. That requires adequate situation awareness. According to Endsley (1995) there are three levels: first the "Perception Of Elements In Current Situation", secondly the "Comprehension Of Current Situation" and the "Projection Of Future Status" at last (p. 35). As the VOs contain a representation of current and future state it should provide for situation awareness on all levels. Because the display has not been tested before, it is of interest if people actually understand when they are in conflict. Thus the question was whether people derive alternatives of reactions to avoid a conflict using VOD-CA and if they react accordingly.

Method

Setup

An explorative study was conducted to investigate people's perception of VOD-CA and their ability to fly safely using the display. Nineteen students mostly with a background in engineering (one female and 18 male) at a mean age of 25.2 years participated in the study. They had at least basic experience in flight simulations. In the study the participants flew at a desktop based simulator with two screens one above the other. A yoke, pedals and a thrust lever were available for flight control.

X-Plane 10 was used as the flight software and displayed on the top screen while VOD-CA received live data from X-Plane and was directing its output to the lower screen. Participants were provided with an outside view, the standard flight instruments in a glass cockpit and VOD-CA in addition. A Cirrus Vision SF50 jet, which is the standard aircraft in X-Plane, was used as flight model. Participants were not provided with a navigation display and had no spatial reference.

Scenarios

There were three tutorial scenarios and seven test scenarios. Every scenario was initialized in mid-air near Frankfurt am Main (Germany) travelling with a speed of 210 knots to the north. To reduce variance, the altitude of intruder and own aircraft was fixed at 10 000 feet so only lateral changes of track and speed were allowed. In the tutorial scenarios there was only one other aircraft that either stayed on course for the whole time or turned after a while. In both cases, an own ship reaction of the participant was necessary to prevent the conflict. The traffic in the following test scenarios consisted of six other aircraft with at least one future intruder. Every scenario lasted about two minutes.

Figure 2 shows an example scenario with the tracks of four intruders and the own aircraft. The aircraft pass without any separation loss.

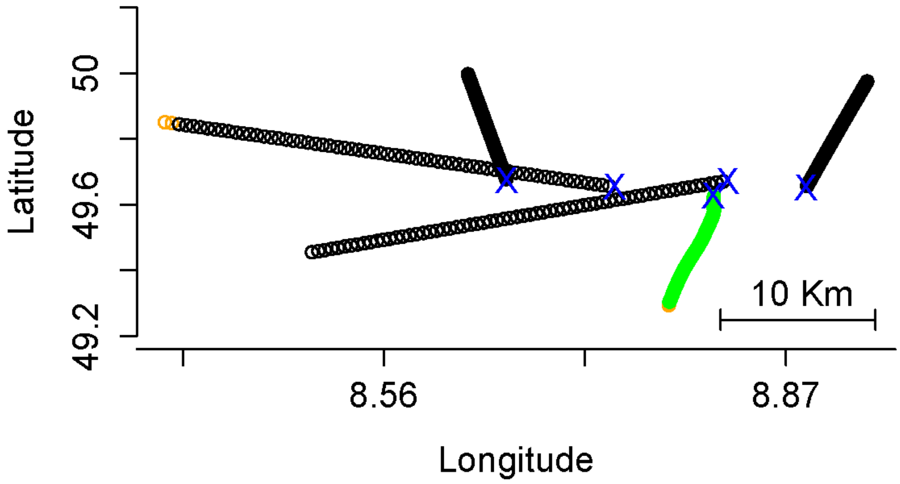

Figure 2. Example of a test scenario (showing only 4 intruder aircraft). Circles represent the locations of the aircraft at discrete time points, each five seconds apart from the last. The green colored tail illustrates the own ship track. The orange parts indicate the times of being in a conflict with another aircraft.

Experimental procedure

Participants familiarized themselves with the handling of the simulation for about five minutes with standard flight instrumentation. After that, they were briefed about the functionality of velocity-obstacles, followed by the four tutorial scenarios to get to know the new display. Participants were instructed to keep clear of conflicts and to stay separated from other aircraft by at least 3000 meters as the highest priority (3000 meters being the parameter used by VOD-CA to calculate velocity obstacles in the simulation).

The test scenarios were split into two parts. In the first four test scenarios participants' conflict-specific situation awareness was assessed using a SPAM technique (Situation Awareness Present Assessment Method; Durso & Dattel, 2004). In the beginning of every run the participants were asked whether they were currently in conflict and if so how they could deconflict. In case of no present conflict participants were asked to identify manoeuvres which would result in a conflict. The simulation was paused in the meantime. After a specific time, in which the participants were allowed to deconflict the situation if necessary, they were asked questions about direction, relative position and conflict potential of intruder aircraft, assessing further situation awareness and display comprehension. Additionally, participants were instructed to notify at the same moment they spotted a velocity change of one of the surrounding aircraft while flying. The second part of the test consisted of tree scenarios with an additional task. Participants should keep their direction to the north if possible, but prioritize staying clear of conflicts like before. Thus it was assured that the scenarios came out as intended. Every run lasted about two minutes. The overall sequence of scenarios was the same for each participant. The whole testing session took at least 90 minutes

Measures

For situation awareness measures, the answers to the SPAM questions were analysed. In the beginning of every run it was asked whether there was a conflict or not (conflict detection) thus assessing the participant comprehension of the situation. Additionally, participants should tell how to resolve the situation in case of a conflict (conflict resolution) and if there could be a future conflict (conflict anticipation) to assess their projection to the future.

For further display comprehension measures participants were asked about the relative position and track of one of the intruder aircraft. Additionally they should track other aircraft's velocity changes and tell the experimenter as soon as they spotted a change.

Besides the question measures, objective flight performance was measured. The number of conflicts and separation losses as well as the time in a conflict were counted. Moreover the deviation from the initial north track by degrees was calculated.

All measures dependent variables are shown in Table .

Table 1. Measures and dependent variables.

Measures	Dependent variables
Situation awareness	Conflict detection Conflict resolution Conflict anticipation
Display comprehension	Intruder relative position Intruder track Detected velocity change
Flight measures	Number of conflicts and separation losses Time in conflict Deviation from heading to the north

Results

The participants' situation awareness was assessed by SPAM questions. The results are plotted in the upper section of Figure 3. It is shown that every starting situation was perceived correctly. When the simulation was paused while flying the scenario participants answered questions assessing further comprehension of the display and the situation. They should tell the relative position of a certain intruder aircraft and its track which means the direction it was heading for. The relative position was named correctly for 97% of the cases. Only 86% of the questions regarding aircraft tracks were answered appropriately (see Figure 3). As a final display comprehension measure, participants were required to spot when an aircraft changed its direction or its speed. As Figure 2 shows at least 81% of the velocity changes were detected.

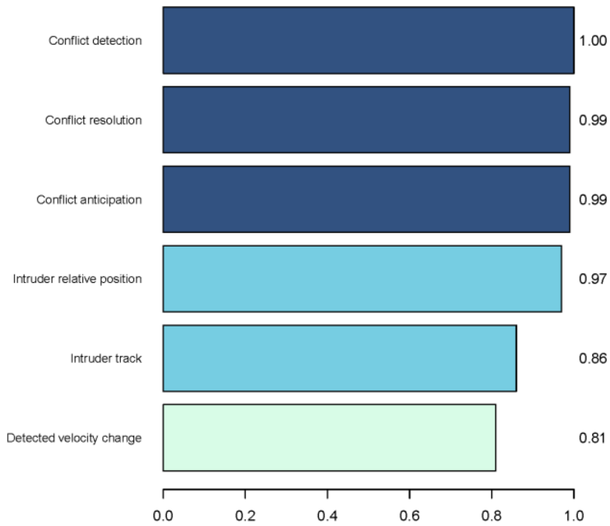

Figure 3. Situation awareness: Proportion of correct answers

There was also a learning effect. Participants got familiar with the display and answered more questions correctly in the later scenarios.

Moreover it was tested whether participants could fly the scenarios without separation loss. Only one participant went below the set separation minimum of 3000m only in the first test scenario. The rest of the time every participant kept the own aircraft well separated.

Participants chose different ways to deconflict. Figure 4 shows the tracks of aircraft within the same scenario flown by two participants showing two different solutions to deconflict. In the left solution the participant turned hard and flew around the conflicts whereas the right solution was more efficient due to less velocity changes but caused another conflict after one intruder aircraft turned.

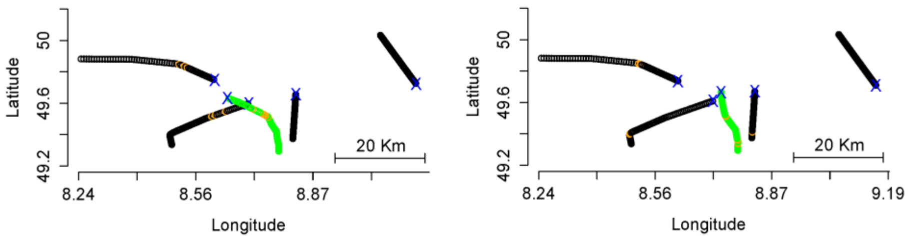

Figure 4. Two different solutions in one of the question scenarios (again showing only 4 intruder aircraft). Circles represent the locations of the aircraft at discrete time points, each five seconds apart from the last. The green colored tail illustrates the own ship track. The orange parts indicate the times of being in a conflict with another aircraft.

In average, there were 3.74 conflicts in the question scenarios and 5.19 in the scenarios with the additional task to keep to the north as long as practicable (see Table 2). However, participants stayed only 4.54 seconds (mean value) inside the conflict area. In comparison, it took them almost two seconds longer to resolve a potential conflict in the earlier scenarios. This might also arise from learning effects.

Table 2. Mean Number and duration of conflicts.

	Question-Scenarios		Additional task scenarios	
	M	*SD*	*M*	*SD*
Mean number of conflicts	**3.74**	3.62	**5.19**	4.70
Mean time in conflict (seconds)	**6.50**	4.25	**4.54**	4.30

At last it was compared how accurately participants stayed to the north. As a measure the mean deviation from zero degree was used. It turned out that the participants deviated by 24.58 degrees in the four questioning scenarios and slightly less in the task scenarios with 23.33 degrees. However, the scenarios differed in complexity so a comparison might be non-informative.

Discussion

The results show that participants can identify conflicts using VOD-CA and react appropriately so they keep themselves safely separated from other aircraft. Information about future hazards and how to avoid them can be derived from VOD-CA directly. In terms of deconflicting and self-separation VOD-CA supports adequate situation awareness on every level of Endsley's model (e.g. Endsley, 1995) indicated by the proportion of correct answers to the SPAM questions. Pilots spot and understand when they are in a conflict, they can identify their alternative manoeuvres to resolve the conflict and act accordingly. The latter can be inferred from the flight data. Only a single separation loss was registered in a first test run. Besides that it could be demonstrated that flying without any loss of separation is possible using VOD-CA.

Furthermore the finding of a learning effect indicates that participants can increasingly familiarize themselves with the display in a test period of 45 minutes. While participants encountered at least one conflict in each scenario, the number of conflicts and the imminence of a separation loss were highly specific to each scenario, making comparisons between scenarios difficult.

Although the display provides the user with an unfamiliar conflict representation, participants learn to use it in a short period of time for self-separation and collision avoidance. Participants were able to spot changes in the velocity of intruding aircraft and act accordingly. The detection of such velocity changes increased with familiarity of the display, e.g. more participants spotted the velocity changes in later scenarios.

Outlook

It was demonstrated that people are able to retrieve the relevant information from the display, and correctly answer the situation awareness questions, future studies could employ for example the reaction time till the relevant information is retrieved and changes are spotted. Another research question is whether the addition of VOD-CA to a cockpit already equipped with a TCAS display increases workload or pilots' head-down time due to attention capture. Also the assessment of users' usability experience could help to revise design aspects.

Some participants stated that they found it hard to derive position information, which they wished to have. As VOD-CA is not designed to display every aspect of the outside world - like exact information about aircraft's positions – but primarily to indicate future conflicts there might be a potential synergy of using it in addition to a spatial positioning display like TCAS. Further research is necessary to investigate how pilots conceive both a spatial and a VO display at once and if there could even be costs due to concurrent display concepts with different qualities of information.

All participants had flight simulator experience, but only 10 out of 19 participants had flying experience, and no professional pilots participated. Whether the display is well received by pilots is therefore a future research question.

Since VOD-CA provides the pilot with additional options for deconflicting, it has the potential to allow for more efficient changes in flight path, as well as more flexible conflict avoidance.

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