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Comparison of Pilot and Automation Generated Conflict Resolutions

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Abstract

This study compares and contrasts conflict resolutions as performed by pilots with and without a resolution decision support tool, and a fully automated conflict resolution tool that generates optimal (smallest path deviation) resolutions. The conflict geometries investigated were all factorial combinations of three levels of intruder aircraft speed, three levels of initial Ownship distance to minimum separation, and nine conflict angles. The resolution decision support tools included dynamic conflict alerting, which indicated whether a proposed path was conflict free, and a dynamic predictor system that showed a fast time depiction of the proposed resolution trajectories. The automation-generated resolutions, computed using a geometric optimization algorithm, served as a benchmark against which the pilot-generated resolutions were compared. Without decision support tools the pilot-generated resolutions were often ineffective, particularly at lower conflict angles. The resolutions tended to be effective when the decision support tools were used. Resolution cost, as measured by added path length, was greater for pilot-generated resolutions (averaging 2.7 nm) compared to the automation-generated resolutions (averaging 1.2 nm). When pilots had the decision support tools, their strategies, as indexed by whether they turned toward or away from the Intruder, tended to be the same as that of the automated system.

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Introduction

New air traffic management initiatives and concepts have proposed that some of the responsibility for maintaining required separation (minimum 5 nm horizontal and 1,000/2,000 ft vertical, in en route airspace) between aircraft be transferred to the flight deck.[1,2] At present, the air traffic controller has full responsibility for ensuring this separation for all aircraft following a filed flight plan under Instrument Flight Rules (e.g., those above 18,000 ft, or those in positively controlled airspace below 18,000 ft). In order for flight crews to assume this new responsibility, they will need flight deck tools that allow them to identify and resolve conflicts[3] (defined as predicted losses of legal separation). Numerous methods are available for conflict detection and resolution.[4]

The ability to shift separation assurance responsibility to the flight deck will strongly depend on the types of decision aids that are provided to the flight crew. At one end of the continuum, flight crews could be provided with a bare cockpit display of traffic information (CDTI), which shows only the location and direction of surrounding air traffic. In this case they would be given responsibility for identifying intruder aircraft (i.e., aircraft with whom they will lose required separation if no action is taken), and then determining a new flight path that would resolve the conflict. At the other end of the continuum, flight crews could be entirely out of the loop, with onboard automation given responsibility for the timely identification of conflicts, as well as the rapid computation and execution of efficient resolutions.

However, if and when flight crews are given responsibility for maintaining separation and resolving conflicts, they will likely be given something in between these two extremes. The design will take advantage of the ability of the automation to rapidly and reliably make complex calculations, and pilot ability to adapt to unforeseen circumstances, new information, or changing goals, not accounted for in the automation.

The present analysis extends a previously reported analysis[5] of the pilot-generated conflict resolution data used in this paper, by comparing how pilots resolve conflicts (with and without a resolution decision support tool) with how an automation-generated solution, computed by a geometric optimization algorithm,[6] would resolve the conflict. The study was restricted to horizontal flight; hence a conflict exists if two aircraft are predicted to be separated by a distance less than 5 nm. All conflict resolutions (whether pilot or automation generated) were provided by heading change maneuvers with no change in speed; in all cases the primary aircraft (Ownship) maneuvered to avoid a conflicting aircraft (Intruder) that maintained its speed and course. The geometric optimization algorithm, which in this study minimizes the added path length for conflict resolution, provides a benchmark solution against which the quality and nature of the pilot-designed resolutions can be assessed.

Five elements were selected to characterize the pilot-generated resolutions: (1) success of conflict resolution; (2) the resulting distance of the two aircraft at closest approach; (3) resolution cost, or how much distance was added to the nominal flight path; (4) response time, or how long it took to design and enter the resolution; and, (5) strategy, or whether the conflict was solved by turning toward or away from the Intruder.

A second goal of the present study was to examine how differences in decision aiding might influence the nature and quality of resolutions. In particular, the study compared resolutions using a CDTI augmented with decision support tools to a more basic CDTI without these tools. These displays have been developed at the NASA Ames Research Center as part of the Advanced Air Transportation Technologies Program.

The basic CDTI displays surrounding aircraft, and alerts the flight crew to conflicts by changes to display symbology. Figure 1 is an example view of the CDTI indicating the positions of Ownship (solid white chevron) and Intruder (outlined chevron) position. It also shows current and proposed flight paths for Ownship, current flight path for Intruder, distance rings around Ownship, flight information at screen top, and command bar at bottom of the screen. In addition, the CDTI also provides fast-time predictions in the form of small white bullets, or pulses, that are synchronously emitted from all aircraft, and which travel along their planned flight path at a speed proportional to their expected ground speed. These pulses are visible along both current paths, and the proposed path, in Fig. 1.

Next, there is the Route Analysis Tool (RAT), which the flight crew can use to design, display, and implement a modification to the current flight plan. Thus this tool can be used to resolve a conflict. When this tool is engaged, there are two other aids that may assist the flight crew in designing safe and efficient resolutions.[7] One aid is Dynamic Conflict Alerting (DCA). With DCA, the system uses a color change to indicate if a proposed route (a route designed but not yet implemented) resolves a conflict or creates a new one. The flight path of the intruder aircraft changes color from yellow (in conflict) to white (not in conflict) when the Ownship's proposed flight path resolves the conflict. This feature only indicates whether or not the minimum distance between the two aircraft will be less than 5 nm; it does not give any information on the numerical value of the minimum distance.

A second aid is the RAT-based Dynamic Trajectory Pulse Prediction (DTPP), which sends a pulse along the proposed flight path in addition to the pulses on the planned flight paths. The DTPP pulse is differentiated by the presence of a 5 nm circle surrounding it, indicating the aircraft's required separation. With DTPP the flight crew can examine how close their proposed route will take them to other traffic. In Fig. 1, the DTPP pulse with surrounding circle is located on the proposed flight path, and DCA is on. Both aids indicate that the proposed Ownship flight path is not in conflict with the Intruder.

Fig. 1 Example view of CDTI

When future disturbances to the flight path (e.g., winds) are not present, it is possible, in principle, to design safe and efficient resolutions with either, both, or neither aid (with neither aid, the flight crew has to cognitively extrapolate or predict along the proposed path). While a previous analysis of this data examined all four of these conditions,[5] only the condition with both DCA and DTPP present (Tools condition), and the condition with DCA and DTPP both absent (No Tools condition) are analyzed in this work.

Pilot-Generated Resolutions

Experimental Design

The study used a partially crossed mixed between- and within-subjects factorial design. There were two CDTI factors: DTPP Pulse feature (ON or OFF), and DCA Alert feature (ON or OFF). However, as mentioned above, only the conditions with DTPP and DCA both OFF and both ON (No Tools and Tools) are analyzed in this work. There were also three scenario factors: (1) initial Ownship (the participant's aircraft) distance to conflict location; (2) Intruder speed; and, (3) conflict angle, the relative angle between the nominal flight paths of Ownship and Intruder. For all conflict geometries, the Ownship speed was 320 kts, and the separation from Intruder at the closest point of approach (CPA) was zero, i.e., an exact collision.

FACTOR	LEVELS
Conflict **Angle** (between-subjects factor)	*Group 1*: 20, 60, 100, 140, 180, 200, 240, 280, 320 (deg) *Group 2*: 40, 80, 120, 160, 180, 220, 260, 300, 340 (deg)
Pulse Status (within-subjects factor)	Pulse ON Pulse OFF
Alert Status (within-subjects factor)	Alert ON Alert OFF
Distance to CPA (within-subjects factor)	30, 45, 60 (nm)
Intruder **Speed** (within-subjects factor)	220, 320, 480 (kts)

Table 1 Experimental design parameters

The four fully crossed within-subjects factors were DTPP, DCA, Ownship distance, and Intruder speed. Since there were a total of 17 possible conflict angles, a full crossing of these angles with the other factors would have generated 612 individual conditions ($2\times2\times3\times3\times17 = 612$), too many to show to subjects within a single period. Therefore the subjects were randomly divided into two groups, with each presented one of the two mirror image subsets of nine angles (see Table 1), resulting in 324 trials per period. These 324 trials were further divided into 4 blocks of 81 trials each, with each block corresponding to one of the combinations of levels of the Pulse and Alert conditions. Within blocks, the order of the trials resulting from the crossing of Angle, Distance, and Speed was randomized, while the order of blocks within a period was randomized across subjects.

Participants

Eight general aviation pilots were recruited from the community as participants. There were no restrictions on number of flight hours, license ratings, gender, eyesight, age, or other factors. All participants were flight instructor rated (which requires at least 250 hrs of flight experience), male, and had vision corrected to 20/20.

Training and Instructions

After reading and signing a standard experimental consent form, participants read a brief description of the study and a set of instructions. The experimenter answered any questions the participants had, and ran them through a set of training trials. All trials were conducted using a Pentium computer and a 21-inch monitor. Participants used the RAT to modify future flight paths, and thus to resolve conflicts. They did this by first using the mouse to click on the RAT button at the bottom of the display (see Fig. 1), which caused a provisional path to be superimposed on top of the current path. They then used the RAT to insert a new waypoint along the provisional flight path and then dragged this waypoint to a desired location. This created a bend in the path, defined by three waypoints. The first waypoint (Wpt1 in Fig. 1) was located on the original path 10.66 nm (2 minutes flight time at 320 kts) ahead of Ownship's position at the time of the RAT initialization. The second waypoint (Wpt2 in Fig. 1) corresponded to the inserted waypoint. The final waypoint (Wpt3 in Fig. 1) was located on the Ownship's original path, 160 nm downstream of the CPA location. Once satisfied, they used the mouse to click on the "Enter" button at the bottom of the display, and the trial ended.

Training trials consisted of 62 experimental scenarios placed in random order. The trials demonstrated several examples of each of the four decision support tool combinations (Alert, Pulse, Pulse+Alert, No Tools) under different conflict angle scenarios. Features of the display were described to the participants, and they were instructed how to use the mouse to turn on the RAT, create a waypoint on Ownship's path, and drag the waypoint to create a proposed solution path. The DCA (Alerting) and DTPP (Pulse) features were also described to the participants, and they were told they would have one or both of these available on some sets of trials, and not on others.

Participants were instructed to generate resolutions according to three criteria, with the following priority: (1) safety (successful resolution); (2) low cost (as measured by added path length); and, (3) timeliness (speed) of determining the solution. When the participants entered a solution path correctly (i.e., resolving the conflict), and in a timely manner, for 10 consecutive trials without requesting any assistance from the experimenter, the training trials were terminated and participants were allowed to begin the experimental trials.

Experimental Trials

The experimental trials were divided into three periods so that participants would have good stopping places to take breaks, if desired. Each period consisted of four blocks of 29 trials, with a total of 348 trials across all three periods. Although no time limits were explicitly given, each trial was intended to be completed within 5 to 10 seconds, and participants generally completed the entire experiment within an hour. The trials within each block represented only one of the four possible decision aiding combinations, but contained all 27 combinations of Intruder speed, Ownship distance to conflict, and conflict angle, with two additional "filler" (non-data) trials at the beginning of each block. Since there were no obvious indicators when one block was finished and another block (with a different set of decision support tools) was beginning, these initial two trials informed the participants that the decision support tools had changed and gave them two initial practice trials. The four blocks within each period were randomly ordered to minimize learning effects across blocks. With the filler trials omitted, there were a total of 324 data trials.

Data Analysis

Due to a computer storage error, data from one subject was lost, and thus the analysis proceeded using the data from the remaining seven pilots. For each trial, the following measures were taken: 1) whether or not the conflict was resolved; 2) distance at closest point of approach between Ownship and Intruder; 3) distance added by the first leg of the resolution path; 4) time needed to enter the resolution (response time); and, 5) whether the participant turned the Ownship toward or away from the Intruder.

Prior to statistical analyses, these measures were combined across the two groups receiving the different sets of conflict angles. This was done by recoding the conflict angles between 200 and 340 degrees into the equivalent angles between –160 and –20 degrees, respectively, and then ignoring the signs in the subsequent treatment of the data. Thus this analysis did not consider the laterality of the conflict (i.e., if the Intruder came from the right or left), but this allowed the data from the two groups to be combined into a single analysis with measures at all the principal angles (20, 40, 60, 80, 100, 120, 140, 160, 180 deg) for each participant.

Automation-Generated Resolutions

The automation-generated resolutions were computed using a variant of the geometric optimization algorithm. A summary of the geometric optimization approach to conflict resolution is presented here; a detailed description is given in Ref. 6. This approach utilizes the geometric characteristics of aircraft trajectories, along with intuitive reasoning, to obtain closed-form analytical solutions of optimal combined heading-speed commands for conflict resolution in the horizontal plane. This solution is optimal in the sense that it minimizes the velocity vector change required for conflict resolution. It can be shown that this results in minimum deviations from the nominal trajectory (subject to certain simplifying assumptions). Solutions for efficient conflict resolution commands using heading change alone and speed change alone are also available; see Ref. 6 for details.

This study focuses on conflict resolution using only heading change maneuvers (with no change in speed). Accordingly, the heading change solutions given by Eq. (18) of Ref. 6 were utilized. It is noted that in general, there are two types of solutions available for conflict resolution in the horizontal plane: one requires the Ownship to pass ahead of the Intruder, while the other requires the Ownship to pass behind the Intruder. For reasons explained in Ref. 6, it is sometimes possible for the Ownship to pass ahead/behind the Intruder by either turning toward or away from the Intruder. Hence, up to four heading change solutions may be available for a given conflict geometry, with each solution providing the same minimum separation (5 nm plus any desired buffer). However, these solutions have different costs, as measured by the additional path length created by the resolution. The version of the geometric optimization algorithm used in this study computed all available (up to four) solutions for a given conflict geometry, and then picked the one with the lowest cost. This automation-generated resolution was considered to be the optimal or benchmark solution in this work.

Table 2 presents key characteristics of the automation-generated benchmark solutions for cases where the Ownship distance to CPA is 60 nm. It can be seen that these solutions generally require the Ownship to turn toward and pass behind the Intruder, except for the conflict configurations indicated by a gray background.

Results

Only the data from the trials where both resolution decision support tools, i.e., DTPP and DCA, were simultaneously present (Tools), or simultaneously absent (No Tools), were analyzed. The dependent variables analyzed were: (1) successful resolution of conflict (required separation achieved); (2) the distance between Ownship and Intruder at the closest point of approach; (3) the resolution cost in terms of distance added by the first leg of the resolution path; (4) the time required to design and enter a resolution; and, (5) whether the pilot turned the Ownship toward, or away from, the Intruder. The results for pilot-generated resolutions are presented below, and are compared with corresponding results for automation-generated solutions (when appropriate).

Successful Conflict Resolution

After participants enter a solution path, the distance is measured between Ownship and Intruder at the point where they pass closest to each other. The solution path resolved the conflict if this distance was 5 nm or greater. The results are shown in Fig. 2, which presents the rate of successful conflict resolution, averaged over the experiment trials, for each of the nine conflict angles used in this study.

Overall, pilots entered solution paths that resolved the conflicts 94% of the time. However, the solutions for conflict angles above 90 deg had no errors, while those below 90 deg had a large number of errors in the No Tools case and a small number of errors in the Tools case (see Fig. 2). The automation-generated resolutions were successful in all cases.

Minimum Approach Distance

In addition to determining whether participants resolved the conflict successfully, the minimum approach distance (distance at CPA) was also analyzed. This was done for all solutions, not just the ones that successfully resolved the conflicts.

The mean minimum approach distance for the Tools case (7.16 nm) was smaller than that for the No Tools case (8.43 nm), and was particularly less for conflict angles between 80 and 140 deg (see Fig. 3). At 20, 40, 160, and 180 deg the minimum distances were close to 7 nm, and rose only slightly in the intermediate angles for the Tools case. However, the minimum distances rose markedly for the intermediate angles for the No Tools case, rising to a maximum of 10 nm. It is noted that all automation-generated resolutions provided a minimum approach distance of 5.1 nm, by design.

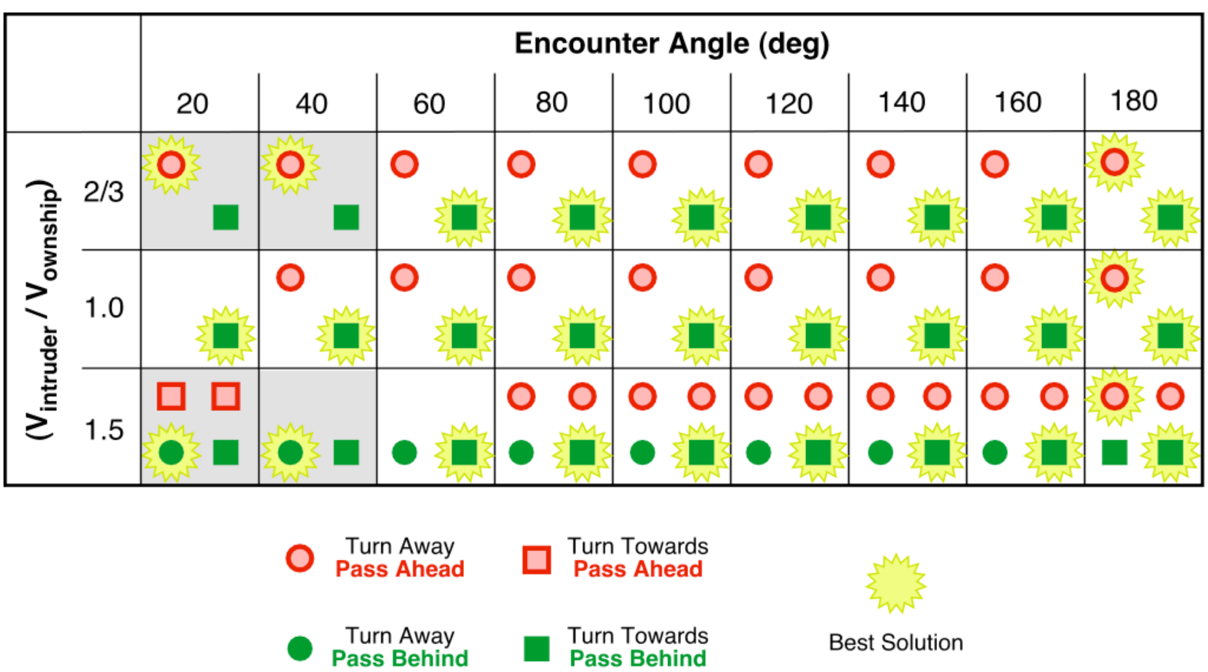

Table 2 Characteristics of automation-generated solutions (Ownship 60 nm from CPA)

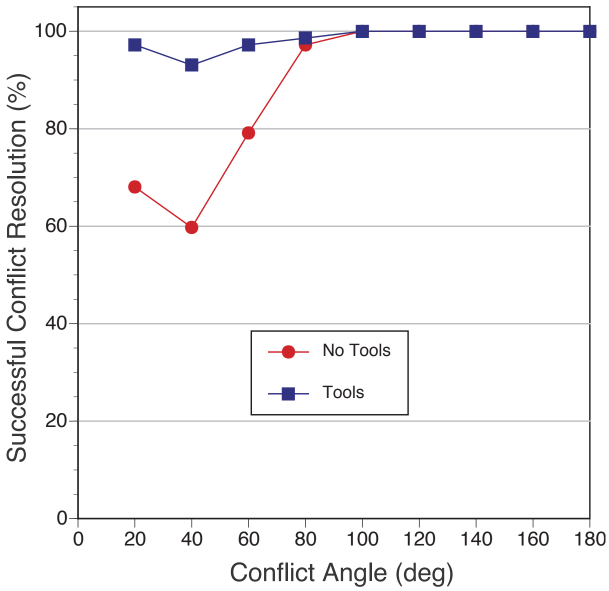

Fig. 2 Rate of successful conflict resolution

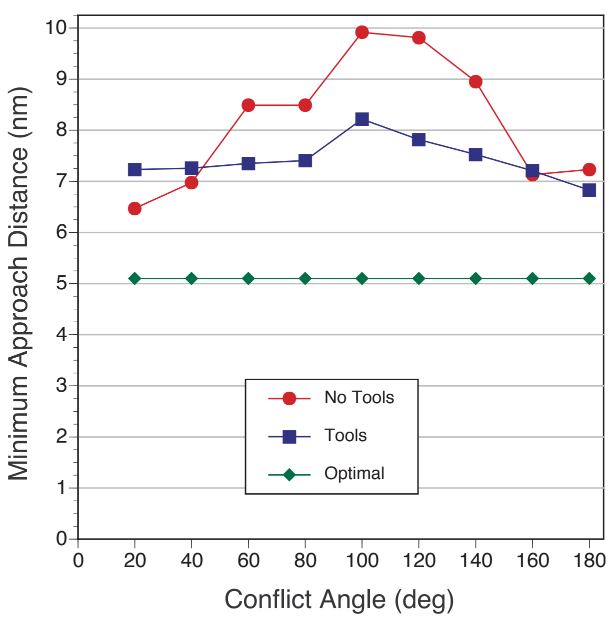

Fig. 3 Minimum approach distance

Conflict avoidance at larger angles (greater than 90 deg) was almost always successful (see Fig. 2), which indicates that pilots are able to resolve these conflicts with confidence even without decision support tools. This is, perhaps, due to the fact that such conflicts can almost always be resolved with only a lateral path separation at the CPA location (drawing the resolution path out laterally from the CPA location). This is especially true for head-on, and near head-on, encounters, (160 and 180 deg), and may account for the high success rate coupled with low values of minimum approach distance.

On the other hand, small conflict angles (20, 40, and 60 deg) require larger and less simple deviations. That is, successful resolutions to these conflicts require both sharper turns and also intermediate return waypoints that are not just laterally separated, but also longitudinally separated, from the original conflict location. Furthermore, due to the more parallel nature of the original flight paths, it is much more difficult to create solutions with a specified value of minimum approach distance. Overall, these difficulties are probably the reason why some of the pilot-generated solution paths failed to solve conflicts at these low angles.

Resolution Cost

Since the initial paths of Ownship were always straight lines, any deviation from this path would result in an increase in path length. Thus resolution cost is measurable by subtracting the original path length from the final path length. For the present study, the resolution was accomplished by first inserting a single intermediate waypoint, and then by dragging this waypoint away from the original path. Thus there were two legs to the resulting path: an initial deviation to the intermediate waypoint, and a return to the original path.

For this study, resolution cost was evaluated by measuring only the distance added by the first leg. The cost of a solution path was calculated as the additional distance traveled along the first leg of resolution path, relative to the corresponding distance along the original path.

Figure 4 shows resolution cost of the pilot-generated resolutions for the Tools and No Tools conditions, as well as the cost of the automation-generated resolutions (calculated by the geometric optimization algorithm). For the Tools and No Tools graphs, each data point represents the cost, averaged over the experiment trials, at a conflict angle. The cost of the optimal resolutions decreases monotonically, but not linearly, with conflict angle, with an average added distance of 1.21 nm. An approximately similar pattern was found for the Tools case, although the average added distance was 2.55 nm. The pattern for the No Tools case was much less similar, with the added distance initially rising to a peak at 60 deg, and then decreasing, with an average added distance of 2.85 nm. For the No Tools case, these smaller path deviations at 20 and 40 deg were correlated with lower rates of successful conflict resolution (see Fig. 2) and smaller values of minimum approach distance (see Fig. 3).

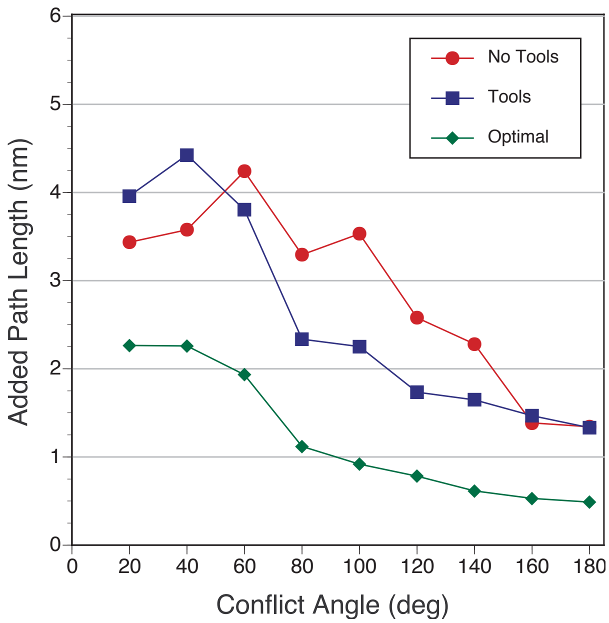

Fig. 4 Resolution cost (added path length)

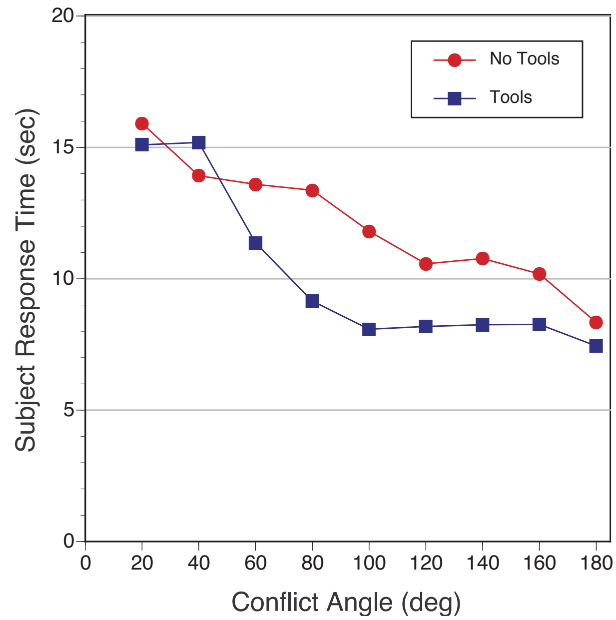

Fig. 5 Subject response time

Response Time

Figure 5 shows the time required by the subjects to design and enter a resolution, averaged over the experiment trials, as a function of conflict angle for the Tools and No Tools conditions. There is a clearly monotone relationship between conflict angle and time for both conditions, although the time is clearly higher for the No Tools condition at angles above 40 deg.

Overall, for the No Tools condition, 89% of the conflicts were solved in less than 20 seconds (during which Ownship traveled less than 1.8 nm), and only one solution exceeded a minute. When Tools were provided this rose to 94% solved in less than 20 seconds, and no solution required more than a minute.

Turn Direction

The frequencies of Ownship turns (for conflict resolution) toward and away from the Intruder were analyzed. The results are shown in Figs. 6 – 8; the three figures correspond to the three Intruder speeds used in the study. Each of these figures shows the frequency of turning in the correct (optimal) direction for the benchmark Optimal case, the No Tools case, and the Tools case. The frequency of turning in the wrong (opposite to optimal) direction is not shown, but may be inferred as the unity complement of the data shown.

With some exceptions at the 20 and 40 deg conflict angles, the automation-generated (optimal) resolution requires the Ownship to turn toward the Intruder. Similarly, for the pilot-generated resolutions, there was a strong general tendency to turn toward, rather than

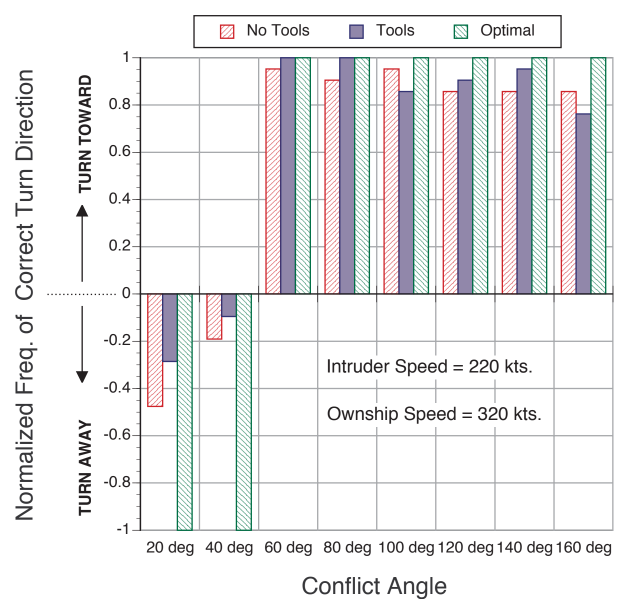

Fig. 6 Turn direction analysis – 220 kt Intruder

away from, the Intruder. This tendency was very strong at conflict angles of 60 deg or higher, at all three Intruder speeds, for both the Tools and No Tools conditions; it is noted that this tendency was more pronounced for the Tools condition.

The correlation between the turn directions of pilot and automation generated resolutions was somewhat lower and less uniform for the 20 and 40 deg conflict angles. The automation-generated resolution requires

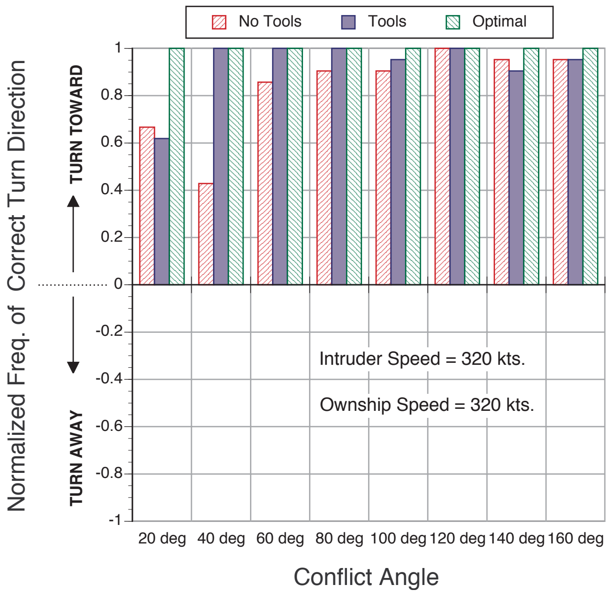

Fig. 7 Turn direction analysis – 320 kt Intruder

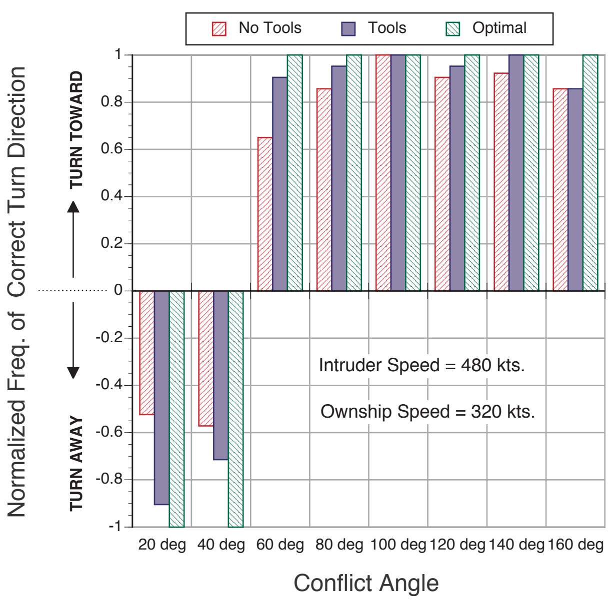

Fig. 8 Turn direction analysis – 480 kt Intruder

the Ownship to turn away from a 220 kt or 480 kt Intruder, and to turn toward a 320 kt Intruder. It is evident from Figs. 6 – 8 that the turn directions of pilot-generated resolutions at 20 deg and 40 deg conflict angles are neither substantially nor uniformly consistent with the turn directions selected by the automation. However, the Tools condition shows a significantly higher consistency than the No Tools condition for the cases with a 320 kt and 480 kt Intruder. For both the Tools and No Tools conditions, the strongest inconsistency in turn direction is observed at a 40 deg conflict angle with an Intruder speed of 220 kts (see Fig. 6). It is worth noting that for both the Tools and No Tools conditions, the 40 deg conflict angle (averaged over all three Intruder speeds), produced the fewest successful conflict resolutions (see Fig. 2).

In order to further explore the turn direction data, Fig. 9 presents a detailed look at all of the inserted waypoints (Ownship turn-back locations) generated by the seven pilot participants for the 20 deg conflict angle in the Tools condition. The three plan views in Fig. 9 depict the data corresponding to each of the three Intruder speeds. Within each view, initial Ownship and Intruder locations are also depicted, as are automation-generated turn-back locations. Symbols are color-coded according to the initial Ownship distance to CPA (red – near, green – mid, blue – far).

Consider the case corresponding to an Intruder speed of 220 kts. Of immediate interest is the fact that there are two clusters of pilot-generated turn-back points, and one cluster of automation-generated turn-back points. The automation-generated turn-back points are proximate to the Intruder trajectory, because the geometric optimization algorithm generates turn-back points immediately downstream of the CPA on the Ownship's modified (i.e., resolution) path. It can be seen that one small cluster of pilot-generated turn-back points is proximate to the automation-generated points, while the majority of pilot-generated points appear to stretch along a narrow band paralleling the original Ownship path, and requiring the Ownship to turn toward the Intruder. A similar pattern can be found in the data corresponding to an Intruder speed of 480 kts, with most turn-back points stretching along a narrow band paralleling the original Ownship path, but requiring the Ownship to turn away from the Intruder. These patterns are consistent with participants attempting to minimize their cross-track deviation from the original Ownship path, but paying much less attention to the along-track location of the turn-back point.

However, the data corresponding to an Intruder speed of 320 kts (equal to Ownship speed) does not show this trend. In fact, here it is difficult to discern any coherent pattern. The figure shows the automation-generated solutions requiring rather significant turns, with a greater than 90 deg turn needed when the Ownship's initial location was closest to the CPA location (corresponding to a very short time to conflict). If the patterns observed at 220 kts and 480 kts do indicate pilots' desire to just minimize lateral path deviation, it may be that the overall difficulty of the 320 kts (equal speed) condition made this simple strategy untenable.

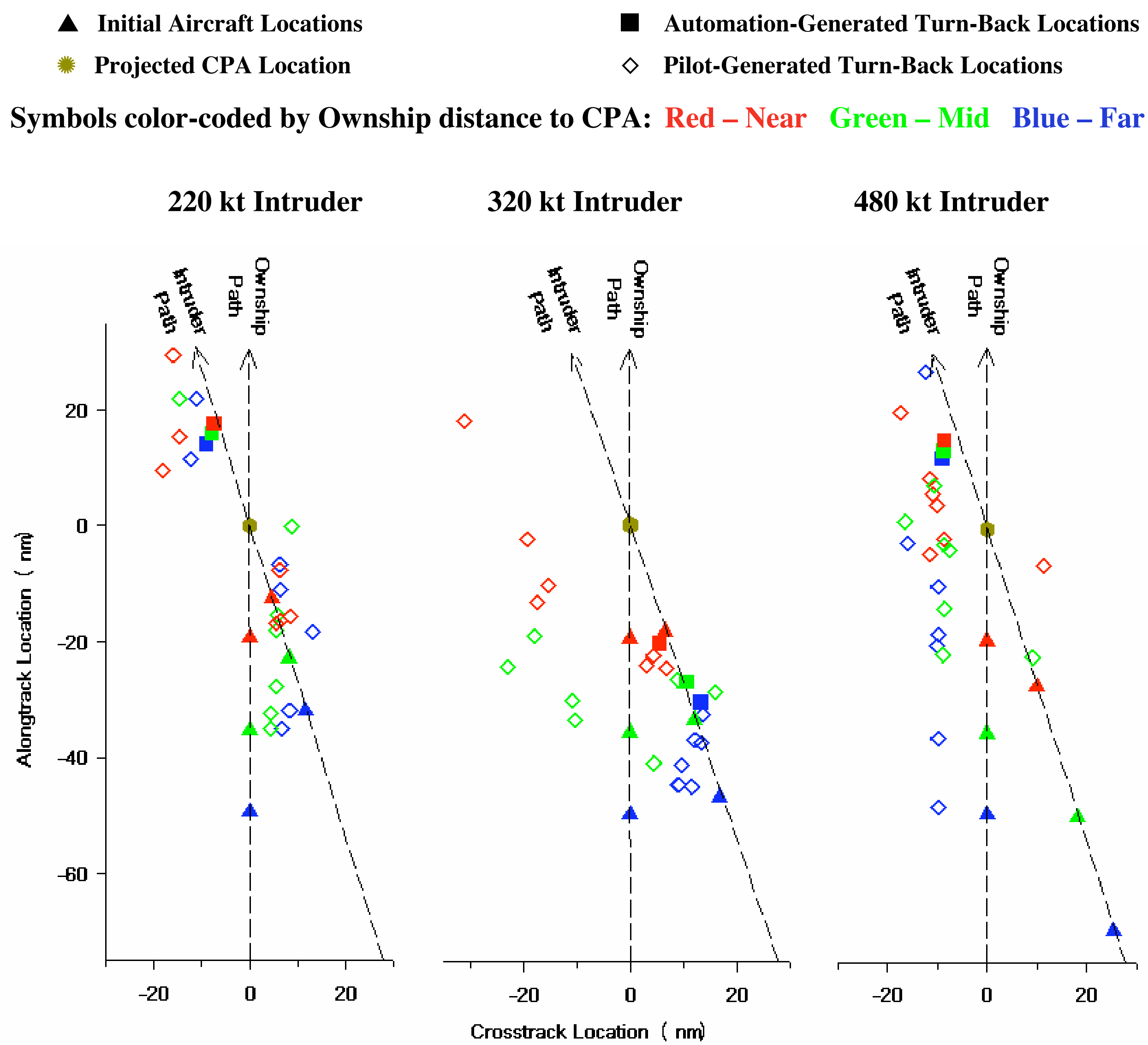

Fig. 9 Plan views of pilot and automation generated turn-back locations for the 20 degree conflict geometry in the Tools condition

Conclusions

In general, pilots did not seem to have difficulty resolving conflicts with angles greater than 90 deg, regardless of whether Tools were present or absent. However, small angle conflicts are difficult to resolve, and in these cases the need for decision support tools is clear. It is also clear that pilots can do this task in an accurate and timely manner for moderately strategic two-party conflicts, particularly with the Tools provided. A comparison of the efficiency of pilot and automation generated resolutions shows a consistent, albeit modest, advantage to the automated resolutions (this is not a surprise since the automated resolutions are optimal). On average the pilot-generated resolutions added about 2.7 nm to the nominal path length, compared with 1.2 nm for the automation-generated resolutions.

It is worth noting that the turn directions for the pilot-generated resolutions were very similar to those of the automated resolutions. This is especially true for conflict angles above 40 degrees. The turn direction selected by the automation is driven by the requirement that the resolution be as efficient as possible. It is not clear if this is the reason that the pilots selected similar turn directions. For example, anecdotal evidence suggests that pilots, when viewing a potential conflict through an aircraft window, prefer to turn toward an Intruder aircraft in order to keep it in sight. Other anecdotal evidence suggests that air traffic controllers resolve conflicts by turning an aircraft toward its conflict partner in order to more quickly achieve diverging paths that are also visually evident. Further analyses are needed to determine if the pilots' strategy of turning toward an Intruder when resolving a conflict using a CDTI reflects a desire to achieve efficiency, or is due to other factors.

A more detailed examination of the low conflict angle data suggests that there may also be a strategy of minimizing lateral path deviation that distinguishes the pilot-generated resolutions. If there is a lack of sensitivity to the influence of the along-track position of the turn-back point on efficiency, then this indicates a potential disconnect between the model used by the automation and the model used by the pilot. Further analyses are needed in order to determine whether this differential model exists.

Finally, it should be noted that pilot reaction to the automation resolutions (generated by the geometric optimization algorithm) was not tested in the present study. The data suggest that the pilots' internal models, and that of the geometric optimization algorithm, tend to result in similar turn directions, but not necessarily in similar turn-back locations. Additional empirical testing is required to determine if these observed similarities and differences have any meaningful impact on pilot acceptance of automation-generated resolutions.

Acknowledgments

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