Risk Perception in Ecological Information Systems

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One issue that regularly occurs in the context of ecological information systems is that these systems can invite operators to migrate to the limits of system performance. This could lead to the assumption that ecological systems are thus inherently unsafe. We argue, however, that the source of this issue is tied to a modeling problem of the work domain. That is, the majority of ecological systems predominantly model the physical or causal structure of the work domain, thereby neglecting the intentional structure. Many complex systems contain a mix of physical and intentional (i.e., rules, procedures, and regulations) that contribute to safe operations of those systems. The work described in this paper examines how visualizing intentional information in an ecological synthetic vision display affects pilot behavior, decision-making, and safety in a terrain avoidance task. An experiment with 16 professional pilots showed that adding an intentional constraint increases the clearance during terrain avoidance and gives them more insight into the terrain avoidance task enabling them to make better decisions.

Cognitive Systems Engineering (CSE) (Rasmussen, Pejtersen, & Goodstein, 1994) and Ecological Interface Design (EID) (Vincente,1999) paradigms are commonly regarded as guiding frameworks to develop 'transparent' automation, allowing human agents to monitor the machine and fluently re-direct machine activities warranted by the demands of the situation. The rationale is to let the computer provide the human agent a set of constraints, rather than an explicit solution, that is directly visible on the human-machine interface, within which any action is possible to solve a problem. Such an approach is seen as more robust and resilient, and can be contrasted with a 'brittle' approach that provides optimal advice most of the time, but fails spectacularly in a few cases.

Although empirical studies have shown that such information aids enable the human to have a better system understanding and a better notion of the physical limitations, possibilities, and relationships within the work domain, humans often tend to propose actions that are suboptimal, good enough, or even "pushing the envelope" (Rasmussen, 1997). For example, Borst, Mulder, and Van Paassen (2010) showed that their ecological synthetic vision display (SVD) invited pilots to systematically violate minimum terrain clearances. This could lead to the assumption that ecological information systems are unsafe and can 'promote' risky behavior.

Although we share the same concern about seeking out the limits of performance, we believe that the risky behavior is tied to the scope of the work domain analysis that is modeled rather than the EID framework itself. That is, the majority of ecological systems predominantly model the physical or causal structure of the work domain, thereby neglecting the intentional structure (e.g., rules, procedures, and regulations) (Hajdukiewicz, Burns, Vicente, & Eggleston, 1999). For example, aviation safety is not only accomplished by the technical systems on board an aircraft, but also by standardized communication and coordination protocols, procedures, and airspace organization. So when the scope mainly includes the causal constraints, the 'physical structure' in the environment will be made compelling and this can cause people to pursue these physical boundaries, leaving little room to prevent accidents. On the other hand, however, when the scope is too much on the intentional constraints, the system will generally be safer, but the operational range of physical systems can be significantly limited to effectively solve problems in novel situations. The EID approach, however, can also be used to make both the physical and the intentional constraints visible and it can also manipulate the relative salience of those constraints.

In this paper it is investigated how visualizing intentional constraints in addition to physical constraints affect pilot behavior and decision-making in a terrain avoidance task when utilizing an enhanced SVD. As such, it aims to answer the following question: when pilots are explicitly confronted with intentional constraints in addition to physical constraints, will they make 'better' decisions and will they better understand the risks involved in those decisions? The work in this paper is essentially a repetition (in some aspects) of the experiment conducted by Borst, Mulder, and Van Paassen (2010) with the addition of an explicit visualization of the required minimum safe altitude above terrain.

Experiment

An experiment has been conducted to investigate how pilots will respond to adding intentional information to an EID display. Building on the experiment by (Borst et al., 2010), a terrain avoidance task with an SVD was chosen. As an intentional constraint, the minimum terrain clearance was chosen which specifies the minimum height a pilot needs to have above the terrain below the aircraft. The participating pilots were put in situations where climbing over the terrain was the only viable option.

Subjects

A mix of 16 recently graduated and commercial pilots participated. Their average age was 40 years (SD 16.13) with an average experience of 3370 flight hours (SD 3923.07). Four of them were TU Delft/NLR test pilots. One of them was a former military F16 test pilot.

Apparatus

The experiment was conducted in a fixed base flight simulator. The display was shown on an 18 inch monitor located in front of the pilot. An outside visual consisting of fog and cloud fragments was projected on the front and side walls to provide some sense of motion. The aircraft model was controlled by a right hand hydraulic side stick and a throttle quadrant on the left. The throttle contained the trim switch, auto pilot disconnect switch and HSI center button. A mode control panel on top of the instrument panel was used to control the HSI course. A non-linear six degree of freedom Cessna 172 model was used for the experiment. Pitch, roll and throttle commands were directly controlled by the pilot. To compensate for the lack of rudder pedals, a side slip controller was implemented to minimize side slip and engine torque effects. Two different performance settings where used during the experiment. During normal performance runs, the model operated in a normal International Standard Atmosphere giving the normal performance at the altitudes flown. In the reduced performance mode, the aircraft performance corresponded to what would be expected at low density altitude conditions. In this mode, climb performance decreases significantly with altitude.

Display

The display used in the experiment is shown in Figure 1. It is based on a Garmin G1000 NAV III augmented with a synthetic vision system. Three additional cues were added for the baseline display. The flight path vector (FPV) indicating the geometric flight path which provides immediate feedback to the pilot about his current trajectory. If the FPV is pointing at the synthetic terrain, the aircraft will impact the ground at that position if the pilot does not take any further action. The maximum sustained climb angle at full power is shown by a wide green bar (no. 3 in Figure 1) this indication immediately shows whether the aircraft is able to clear the terrain at maximum climb performance. When this line is below the synthetic terrain, the pilot will not be able to climb over it and will have to choose a different maneuver. Similarly the current maximum climb angle (no. 2 in Figure 1) is the maximum climb angle that can be sustained with the current power setting/throttle position. With this indication, the pilot gets immediate feedback about his current climb performance and is able to climb at lower power settings while still being sure to clear the terrain.

The baseline display is augmented with an intentional layer indicating the minimum safe clearance above the terrain (no. 4 in Figure 1). This layer is created by shifting the synthetic terrain up and drawing it in amber behind the physical terrain. In this way, the layer has the same relationship to the FPV as the original terrain. If the FPV is above the layer, the terrain clearance will be at least the required minimum clearance. An additional advantage of adding the intentional layer to the display is that it improves distance perception of terrain features, something that is very difficult in traditional SVDs. Because the layer has a fixed height, its resulting thickness on the display is an indication for the distance to the terrain. Even tough the relationship between distance and thickness is non-linear, it can aide in a crude estimation of the actual distance of terrain features

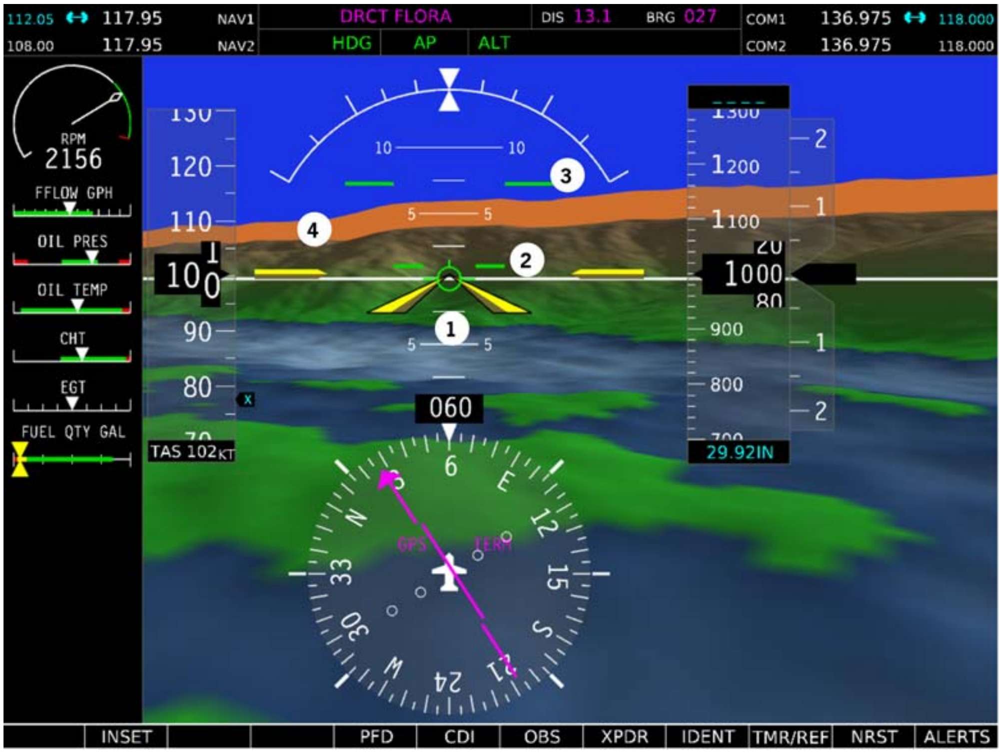

Figure 1: The SVD display, showing: 1) The flight path angle, 2) the current maximum sustained climb angle, 3) the maximum sustained climb angle at full power, and 4) the intentional terrain constraint

Scenario

The scenario used for the experiment consisted of an artificial terrain with a number of narrowing fjords. The base of the fjords was at sea level the tops were around 3000 ft. The pilots were told that they flew into the wrong fjord on their way to the airport and are low on fuel by the time they realize their mistake. Each experiment run started in one of the predetermined initial locations at an altitude below the surrounding fjord tops. From this starting position it was impossible to get to the airport without climbing over the terrain. A navigation beacon was placed in between the initial positions and the airport to provide a navigation reference that could be reached in three to five minutes eliminating the need for long cruise segments to reach the airport.

Pilots were instructed to navigate the waypoint and keep clear of the terrain in a way they considered safe and comfortable. Pilots were not given minimum altitude instructions, but they received a map of the area that showed 4000 ft as the minimum safe altitude for the area they were navigating.

Independent Variables

The experiment used three within-subject variables each having two levels: display configuration, scenario difficulty, and aircraft performance. The display configuration was either a baseline display without the intentional layer, or a display with the intentional layer visible. Two levels of difficulty are used. Easy conditions start with enough margin for a straight climb towards the beacon. The hard conditions required immediate full power and a maximum performance climb to avoid the intentional layer. Two levels of aircraft performance were used. With normal performance, climb performance remains almost constant during the first 4000 ft of the climb. With the reduced performance, climb performance severely deteriorates above 2500 ft.

The order in which the display configuration was tested was used as a between-subject variable. One group of pilots started with 8 runs using the baseline display and then moved the augmented display. The other group started with the augmented display and moved to the baseline display afterward.

Dependent Measure

The main dependent measure of this experiment is the minimum terrain clearance during the experiment run which can be interpreted as a measure of safety of the maneuver.

Next to this objective measure, notes were taken during each run describing the pilots choices. After each run, pilots provided feedback about their strategy and choices.

Experiment Design

The pilots were divided in two groups, one started without the intentional additions, the other started with the intentional additions enabled. Initially there were 18 pilots divided equally among both groups, but during the experiment, two pilots failed to complete the experiment. This resulted in nine pilots starting without intentional additions and seven pilots starting with intentional additions.

Each pilot flew eight conditions per block (two difficulty levels, two performance levels, and two repetitions). The conditions where randomly distributed based on a Latin square matrix to avoid effects based on the condition order. Different Latin squares were used for both blocks. At the end of the experiment, 256 samples were collected (2 * 8 * 16).

Procedure

The experiment started with a training phase to familiarize the pilots with the display, flight controls, and aircraft model. During training, the pilot could fly around freely in a training database and got an explanation on the display features. Once the pilot was familiar with the added features, the measurement runs began. No task specific training was done, only display familiarization.

Before each measurement run started, the pilots were instructed to set the throttle to the trim position. Once the run started, the autopilot maintained altitude and airspeed for five seconds. During this time, the pilot was asked to observe the situation. After the autopilot disconnected, the pilot had to confirm the disconnect by pushing a button and navigate the aircraft towards the navigation beacon. Once they were close to the beacon, the run ended and the pilots provided feedback about their strategy during the run.

At the end of the experiment pilots were asked to complete a questionnaire to evaluate the overall experiment.

Results

To analyze the objective clearance measure, a repeated measures Analysis of Variance (ANOVA) has been performed. To simplify the analysis, the results from the repetitions were averaged per condition resulting in eight data points per pilot. This assumption should not distort the results too much since the majority of the pilots showed a reasonable consistency between the repetitions in terms of strategy and minimum clearance. Figure 2 shows a summary of the minimum clearance values for all pilots per condition together with the mean and standard deviation per condition. The figure shows that the minimum clearance increases when the intentional constraints are visible. This effect is confirmed with the ANOVA showing an effect for the display type ($F(1,14)=5.44$, $p < 0.05$). No significant interactions were found for the difficulty and performance variables with the display type. The display order did not have a significant effect ($F(1,14)=0.687$, $p=0.064$) but was close to the $p=0.05$ significance level. Further research with more pilots might reveal an actual influence of the display order. During the post experiment questionnaire one of the pilots remarked that his strategy without intentional layer had changed by starting with the intentional layer enabled.

The only other significant effects were the main effects of the complexity ($F(1,14)=23.446$, $p<0.01$) and performance ($F(1,14)=15.332$, $p<0.01$) variables. This confirms that the task became more difficult both with decreasing performance and with increasing difficulty.

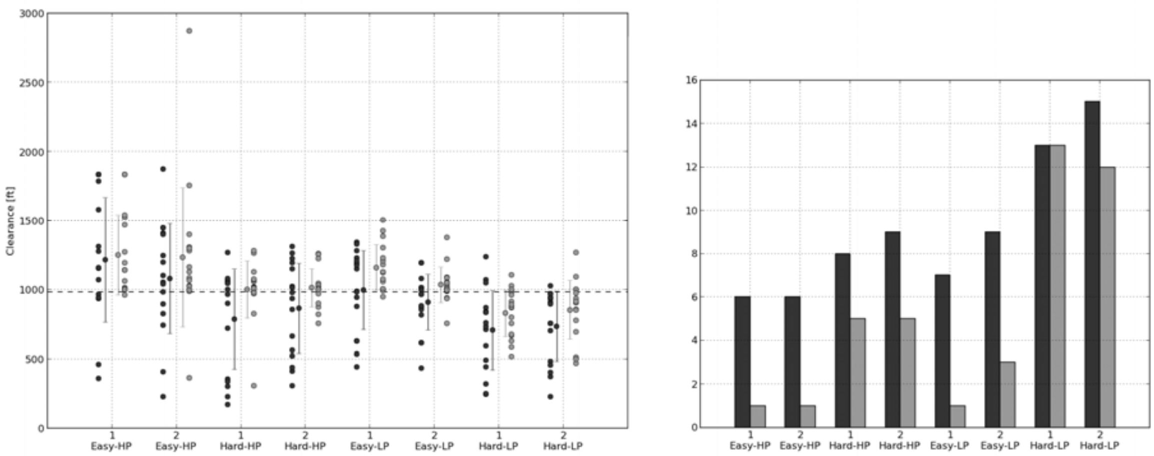

Figure 2: Minimum clearance includeing mean and standard deviation (left) and number of clearance violations (right). Baseline values are black, intentional layer enabled values are gray.

At the end of the experiment each pilot answered four questions about their experience with the intentional constraints. 14 pilots responded positively to the question if the intentional addition makes the terrain avoidance task clearer. The main reasons they give is the increase in situation awareness, better perception of height above the terrain, and a reduced mental load when planning a terrain avoidance maneuver. One pilot stated that the procedural addition makes the task more restrictive. One pilot indicated that the intentional layer was distracting and had not been used.

The question whether the intentional layer changes their strategy, was confirmed by 12 pilots. The majority indicates that the additional information presented enables them to quickly see the lowest regions of the terrain and also provides immediate information about the power required to reach the safe altitude. One pilot also noted that he intentionally put his flight path in the intentional layer because he felt comfortable with a lower clearance and the layer gave him a good indication what pitch angle was required to satisfy this clearance. Of the pilots answering no, two indicated their strategy remained the same but they used the intentional layer as a confirmation of their strategy.

Every pilot, except the one that ignored the intentional constraints, felt that the perceived level of safety increased when the intentional constraints were visible. This mainly happens because the safety margin becomes explicit in the display enabling them to directly assess the risk involved. One pilot noted that adding the procedural constraints *takes the guessing out of flying*. The final question whether the pilots considered the procedural additions useful was answered positively by all but on pilot and is in line with the answers to the previous questions.

Discussion

The main objective of the experiment was to investigate the effect of visualizing intentional constraints in addition to causal constraints helps pilots in making better decisions. Better decisions in the context of this experiment means respecting the minimum safe clearance as much as possible. Analysis of the objective clearance parameter confirm this hypothesis. There is a significant increase in minimum clearance when comparing the intentional addition to the baseline display.

To get more insight in this change in clearance, Figure 2 shows the clearance values of all pilots per condition and the number of pilots that flew below the minimum safe clearance. In the Easy-HP condition all but two pilots fly above the minimum safe clearance when the intentional layer is enabled. In their feedback and through observation it became clear that with sufficient performance and margin pilots will treat the amber band as if it is actual terrain and will avoid it. Only one pilot deliberately ignored the layer and accepted a clearance of less than 500 ft. The second pilot violating the minimum clearance kept his FPV close to the amber layer resulting in a very brief excursion just below minimum clearance.

In the Hard-HP conditions, the same strategy surfaces. Pilots are more inclined to try to meet the minimum clearance with the intentional layer enabled. There are more violations than in the Easy-HP condition, but they are all except one minor violations. By steering into the top of the amber band pilots could make an informed choice about sacrificing a little clearance for a quicker route towards the airport.

In the low performance conditions, the same trends can be observed as in the high performance conditions. The main difficulty in the low performance conditions is that the climb performance significantly decreases during the climb. A number of pilots failed to note that there was not enough margin between the maximum climb performance and the amber region, but even in these cases the amber band shows that they are closer to the top of the minimum clearance and can continue relatively safe.

From the figures it can also be seen that with the baseline display a number of pilots flew with less than 500 ft clearance. For two pilots this was a deliberate choice, the other pilots were mainly unaware of their actual clearance. Not counting these deliberate violations would leave approximately 10 instances where pilots flew below 500 ft. This number is only a third of what Borst, Mulder, and Van Paassen (2010) found in a previous experiment with an EID terrain awareness display. The main reason for this difference is probably the fact that pilots had more freedom to perform an escape maneuver.

Trough the observations, post run feedback of the pilots, and the questionnaire it became clear that the majority of the pilots used the intentional addition to either improve or change their strategy in solving the conflict. The way in which they fit the intentional addition in their strategy can differ but they all indicated that it enhanced their analysis and awareness of the task at hand.

One drawback of the current intentional representation surfaced during the experiment. Once a pilot flies below the minimum clearance, the whole top part of the SVD is filled with the amber color. Once this happens, it is no longer possible to directly perceive the difference between a minor violation close to the top of the intentional layer or a dangerous violation close to the terrain. In the future this could be resolved by using different shades of amber to indicate different clearance levels in the intentional layer.

Conclusion

The main objective of the experiment was to investigate the effect of visualizing intentional constraints in addition to causal constraints helps pilots in making better decisions. Better decisions in the context of this experiment means respecting the minimum safe clearance as much as possible. Analysis of the objective clearance parameter confirm this hypothesis. There is a significant increase in minimum clearance when comparing the intentional addition to the baseline display.

Acknowledgments

The authors would like to thank all pilots participating in the experiment for their time, effort, and professional feedback.

References

Borst, C., Mulder, M., & Paassen, M. M. V. (2010). Design and Simulator Evaluation of an Ecological Synthetic Vision Display. *Journal of guidance, control, and dynamics*, 33(5), 1577-1591.

Hajdukiewicz, J. R., Burns, C. M., Vicente, K.J., & Eggleston, R.G. (1999). Work Domain Analysis for Intentional Systems. In *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 43, pp. 333-337). DOI: 10.1177/154193129904300343

Rasmussen, J. (1997). Risk Management In A Dynamic Society: A Modeling Problem. *Safety Science*, 27(2), 183-213

Rasmussen, J., Pejtersen, A. M., & Goodstein, L. (1994). *Cognitive Systems Engineering*. Wiley.

Vincente, K. J. (1999). *Cognitive Work Analysis*. Lawrence Erlbaum Associates, Inc.