Modeling Human and Animal Collision Avoidance Strategies

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In this paper we propose technical solutions for overcoming pilots' limitations in handling collision situations in visual flight. An analysis of pilots' requirements for future development of such systems shows that a surprisingly large proportion of pilots would prefer automated systems which will allow decision and performance of the avoidance maneuvers, and recapturing of the initial route by the autopilot. For building up a model of collision avoidance we reviewed previous findings on collision avoidance strategies of pilots, air traffic controllers and pedestrians. Additionally, we reconsidered studies on collision avoidance strategies of birds and insects. Finally, we discuss new challenges for future cockpit technology and flight training methods to improve collision avoidance management and safety of VFR pilots.

Making use of powered vehicles humans navigate in spacetime zones to which they were not predestined by their natural abilities. In their natural eco-systems animals and humans are adapted to protect their personal space from intrusion. However, as accident and incident related to the use of powered vehicles show, humans are vulnerable to collisions within the artificially created spacetime despite existent technology, procedures and training.

The rate of midair collisions involving pilots flying according to visual flight rules (VFR) remained constant despite an overall decline of General Aviation accidents in the past decades (AOPA, 2009). An analysis of midair collisions in VFR (Taneja & Wiegmann, 2001) showed that all midair collisions occurred under visual meteorological conditions, 35.4 % involved a head-on configuration and many resulted from an overtaking maneuver. In 85% of cases the reported cause of accident was inadequate look out by the pilot(s).

There are many factors which make detection of interpretation of conflict situations difficult, despite good visual meteorological conditions. However, technological solutions such as the new collision warning systems for VFR (e.g. FLARM and ADS-B based systems) which display traffic and warnings are expected to improve flight safety. We implemented such a system in flight simulator (www.flightsimulation.tugraz.at) at Graz University of Technology and evaluated the benefits and limitations of new collision warning systems for VFR pilots.

In the following we present briefly the main results of our study and compare findings from the literature which evaluated collision avoidance preferences of pilots, air traffic controllers and pedestrians. We also mention avoidance strategies of insects and birds. These are excellent flyers, naturally adapted to live in flocks or swarms, and manage to fly safely without recurrent proficiency checks, instruments, or warnings. Finally we draw out implications for modeling human and animal collision avoidance behavior.

On collision avoidance tactics in humans and animals

Study of pilots' initial collision avoidance responses in visual flight

In a simulator study we evaluated the initial responses of 18 VFR pilots to single and multiple traffic approaching at the same altitude (see also Haberkorn, Koglbauer, Braunstingl & Prehofer, 2013). Traffic was displayed on the visual system of the simulator and on a moving map display which generated a warning 24 seconds before the closest point of approach. Pilots were flying at 6000 ft above ground level.

Pilots' responses for two conflict geometries are illustrated in Figures 1 and 2. A short remark for the interpretation: according to aviation regulations the correct evasive maneuver in case of frontal conflicts is a turn to the right, meaning in our case a positive change of heading. Approaching aircraft (from the left, 290 degree) did not respect the priority rules being non-cooperative and forcing the pilots to induce necessary avoidance maneuvers. As illustrated in Figure 1, where the oncoming aircraft was approaching head-on from 10°, preferences for descends combined with evasive turns to either left or right can be noticed. In the multiple traffic condition (Figure 2) pilots' preference for descents and a right turns can be observed.

Traffic load influenced significantly pilots' reactions. The amplitude of pitch changes and the changes of vertical speed regardless of direction were higher for multiple conflicts than for single conflicts. The magnitude of heading changes decreased from the first to the second and third trail. In conditions of multiple traffic reaction times to traffic warning were longer, mental workload increased, whereas spare mental capacity and anticipation decreased.

Thomas and Wickens (2005) also found a preference for vertical evasive maneuvers in level conflicts with approach angles of less than 120°. Climbs were most preferred (45%) followed by level flight (31%) and descents (25%). Only in 55% of cases pilots avoided to the right. Actually, a large amount of previous studies with pilots confirms a preference for vertical maneuvers (Abbott, Moen, Person, Keyser, Yenni & Garren, 1980; Merwin & Wickens, 1996; O'Brien & Wickens, 1997; Wickens & Morphew, 1997; Gempler & Wickens, 1998; Wickens & Helleberg, 1999; Helleberg, Wickens & Xu, 2000, Alexander & Wickens, 2001). Palmer (1983) reported a preference for vertical versus lateral only under time pressure. However, results are not conclusive. There are also studies showing preferences for lateral collision avoidance maneuvers (Palmer, 1983; Ellis, McGreevy & Hitchcock, 1987). Only few studies showed preferences for changing airspeed maneuvers (Chappel & Palmer, 1983).

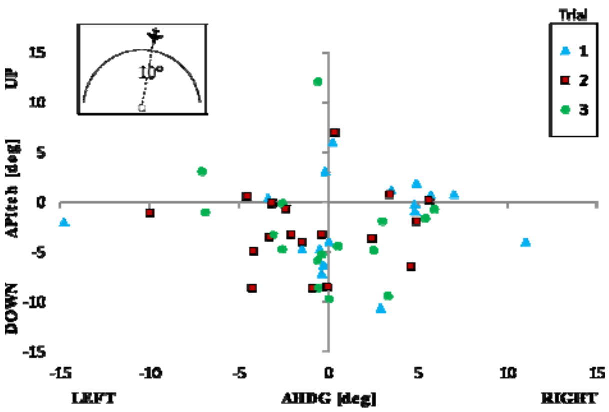

Figure 1. Pilot initial responses to an aircraft approaching from 10 degree at the same altitude. Changes of pitch and heading, 5 seconds after reaction begin.

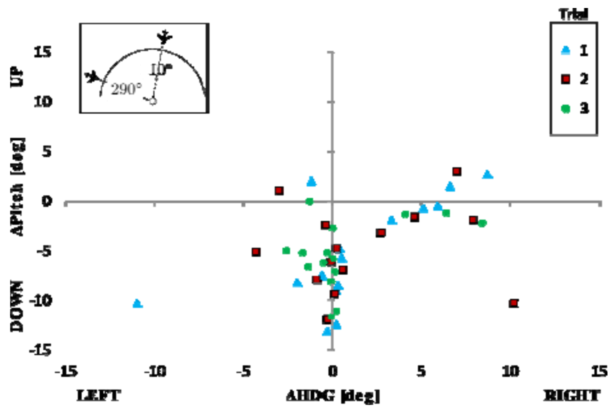

Figure 2. Pilot initial responses to aircraft approaching from 10 and 290 degree at the same altitude. Changes of pitch and heading, 5 seconds after reaction begin.

Collision avoidance preferences of air traffic controllers and pedestrians

Studies with air traffic controllers showed similar results. Rantanen, Yang and Yin (2006) found a preference of student controllers for climb (39.9%) and descend (35.7), whereas speed adjustment was used in 19.4% of cases (increase 12.8% and decrease 6.5%). Heading changes were used only 5% with no differences between left and right.

The above mentioned studies address human interactions with artificial systems and spacetime dynamics which exceed their natural environment. For getting a better picture of "natural" human collision avoidance preferences we are also investigated empirical findings with pedestrians. Interestingly, studies of pedestrians avoidance strategies show preferences for speed changes (Blue, Embrechts & Adler, 1997), maintenance of current direction (Antonini, Bierlaire, and Weber, 2006) or minimization of the angular displacement (Turner and Penn, 2002) and smooth non-linear trajectories (Bierlaire et al. 2003). If a head-on collision is imminent both pedestrians tend to make a side-step (Helbing, Molnar, Farkas, and Bolay, 2001). Some findings show that pedestrians tend to pass on the right in head-on conflicts (Goffman, 1971), but other reported that pedestrians passed on both left and right with equal probability (Daamen and Hoogendoorn, 2003).

The tendency to minimize heading changes after more repetitions of the same avoidance maneuver was found in both our study with pilots and studies with pedestrians (Antonini, Bierlaire, and Weber, 2006; Turner and Penn, 2002). These findings suggest a cost-benefit evaluation in choosing the avoidance maneuver. Together with the general preference for vertical maneuvers these findings indicate a tendency to protect the initial route or an economic bias in choosing the avoidance tactic.

Collision avoidance strategies of birds and insects

For a better insight in evolutionary-proven strategies we searched for information on animal collision avoidance behavior. We know that birds and insects are well adapted to maintain separation from their flock neighbors and obstacles or to escape predators. Although their brain is simpler than the human brain, their 3D collision detection and avoidance mechanisms seem to be more effective (Miller, Ngo & van Swinderen, 2012). This was the reason for development of new bio-inspired collision detection systems (Stafford, Santer & Rind, 2007a; 2007b).

Interestingly, we found that studies with locusts also show a preference for vertical evasions. For escaping predators and for collision avoidance with another locust during flight locusts perform a gliding dive, ceasing to beat their wings and holding all four wings raised with above the hind wings held slightly swept back (Santer, Simmons & Rind, 2005). During diving locusts decelerate from 4 m/s to 2.5 m/s and lose about 3.5 cm height. For collisions at relative approach speed slower than 3 m/s the dive is preceded and accompanied by other steering movements (Simmons, Rind & Santer, 2010).

The pea aphid (*Acyrthosiphon pisum*) also uses dropping as anti-predator tactic (Lawrence, Fraser & Roitberg, 1990). Research shows that pea aphids are less likely to drop and avoid when they have high quality feeding hosts or when they are in hot and dry conditions and the risk of desiccation is higher. Thus, their tactic can be interpreted in an economic cost-benefit framework. Similarly, the delay of first escape responses of redshank (*Tringa totanus*) flocks was found to be determined by economic reasons. Delay was increasing for low-risk stimuli and decreasing for high-risk stimuli such as hawks (Quinn & Cresswell, 2005).

Another interesting aspect of animal behavior is the spatial organization of flocks. Lukeman, Li and Edelstein-Keshet (2010) observed native undomesticated flocking surf scoters in groups of up to 200 individuals in their natural setting, on water surface. In the horizontal plane scoters changed their speed and deviated sideways for maintaining separation in the flock. They made frequent +/-180 degree head turns to watch their neighbors. The spatial behavior in the flock could be described in terms of short-range repulsion for maintaining separation, intermediate-range alignment and longer-range attraction of the individuals to the flock. The individual position, velocity and trajectory created spatial and angular neighbor distribution plots, showing a concentric structure in positioning, a preference for neighbors directly in the front, and strong alignment with neighbors on each side. Furthermore, scoters were structuring their space to form empty avoidance zones which they use to escape encroaching gulls which attack them to rob their mussels.

We see that flying insects and birds seem to use primarily the vertical plane to escape. Pedestrians and surfing birds prefer speed changes and horizontal escape maneuvers with minimal deviance from the route. Expected costs and benefits seem to influence the deviance from the route and the delay of the escape maneuver.

Considerations for modeling collision avoidance strategies

In our study requirements for future development of collision avoidance systems in VFR were specified with feedback from pilots (see also Haberkorn et al., 2013). Automated aids for detecting traffic conflicts were required by 94.4% of the pilots, whereas automatic generation of an avoidance route was required by 61%. With regard to automatic performance of the avoidance maneuver 58.8% of pilots would prefer the option to abort and 44.4% would prefer the option to approve an automatic evasive maneuver. With regard to automatic recapturing of the initial route after performing the avoidance maneuver 61.1% would prefer the option to abort and 72.2% would prefer the option to approve an automatic maneuver.

From the kinematic point of view collision situations are precisely described in terms of time and distance to collision of two or more vehicles approaching with specific speeds, and optimal routes for collision avoidance can be calculated by algorithms. However, in nature detection and avoidance of collisions is based on intuitive mechanisms. We consider that automatic collision avoidance systems will be accepted only if they do not contradict the intuitive judgment of humans. Thus we attempt to apply basic knowledge about intuitive strategies applied by humans and animals for future development of collision avoidance systems. If pilots will either abort or approve an automatic collision avoidance maneuver, they should be able to evaluate conflict situations and automatically calculated routes in a timely manner.

TCAS reports from commercial aviation show that pilots do not always comply with automatically generated resolution advisories (RA). Coso, Fleming and Pritchett (2011) found that in 8% of 251 cases pilots have not accepted the RA. Mentioned reasons were the contradiction of pilots' attempt to keep the intruder aircraft in sight, the involvement of a third aircraft, or pilots' impression that the RA would direct them into traffic. In other cases pilots added a horizontal component to the RA, which are solely vertical. As Coso et al. (2011) showed, pilots judge more contextual information than TCAS and these judgments influence their compliance with RAs.

Implications for modeling automatic collision avoidance strategies

We propose to include both contextual information and collision avoidance preferences in modeling collision avoidance strategies of future automatic systems.

Contextual information:

- Prioritization in conditions of multiple traffic
- Consideration of non-sensed flying objects and fixed obstacles, terrain, airspace restriction data
- Rules and regulations (e.g. priority according to type of air vehicle, conflict geometry, airport procedures)
- Safety envelope of the aircraft (e. g. airspeed, altitude, pitch, roll, yaw)
- Autopilot features
- Data-link: communication aircraft-aircraft, aircraft - air traffic control

Collision avoidance preferences:

- Display indication: multimodal display (visual and acoustic, to avoid increasing head-down time)
- Timing – for evaluation of both the conflict situation and the proposed automatic avoidance maneuver
- Automation approval and /or override options
- Route protection (minimal heading changes or attraction to the next leg of the route, speed changes)
- Use of a vertical component
- Smooth, non-linear trajectory

Trajectory building

The goal of any trajectory planning algorithm is to determine future history of control inputs on the own aircraft under influence of minimizing a cost function (Stengel, 1994). This mechanism should be robust against disturbances such as partial signal loss and wind turbulence.

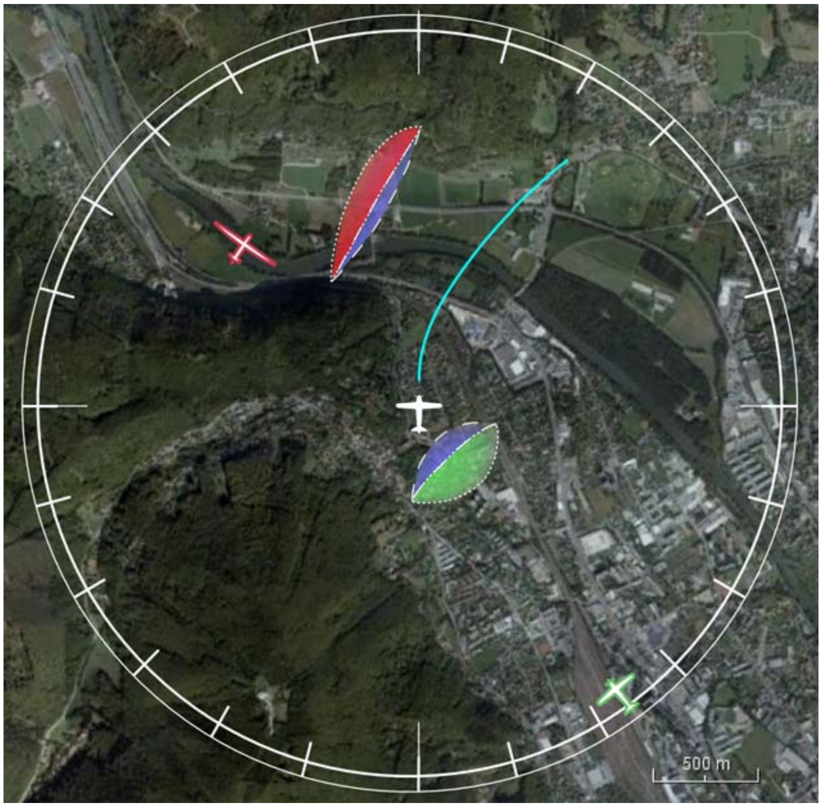

Figure 3. Possible horizontal trajectory to avoid conflict with the glider approaching from the left and a with a powered aircraft from behind by using the volume of intersecting sets as a cost function.

One way to calculate the cost function is to determine volumetric protected zones around each participating aircraft, with shapes and sizes dependend on specific aircraft capability. The cost function is calculated using the volume of intersecting set of protected zones. From all possible control inputs to the own aircraft, candidate-trajectories are selected. These are optimal trajectories in the sense of minimizing the volume of intersecting sets. Trajectories have to be further compared according to context criteria stated above (e. g. rules and regulations, route protection). Furthermore, the energy efficiency of remaining candidate trajectories has to be compared.

In addition the system may use a pilot setup for the pre-selected mode of operation (e.g. horizontal evasion at constant velocity, vertical evasion, evasion by speed changes). Filtering of remaining alternatives could then be performed according to the pre-selected mode. Finally, a trajectory will be chosen and displayed by the system (Figure 3). Pilots will be able to control automation using the approval and override options.

Final Considerations

Although automated collision avoidance in VFR is possible, we expect to encounter certain limitations for future systems. The main limitation originates in the characteristics of airspace destined for VFR flight. Models of obstacles, terrain and airspaces should be considered, as well as sensors for detecting all flying objects, not only those equipped with FLARM, ADS-B or transponder.

Furthermore, we need more research to evaluate pilots' interaction with automatic collision avoidance systems. With respect to human bias in selecting collision avoidance options (e.g. vertical, lateral or airspeed maneuvers) we know little about pilots' acceptance, monitoring and trust in such alternatives when they are proposed by automation.

Additionally, hands-on simulator training for handling automatic collision avoidance systems will be necessary. Training scenarios should include also scenarios with imperfect automation (e.g. flying objects not recognized by the system etc.). For improving safety and efficiency automatic collision avoidance systems should be used and controlled by pilots who are familiar with benefits and limitations of automation.

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Acknowledgments

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