INCREASING ACCEPTANCE OF HAPTIC FEEDBACK IN UAV TELEOPERATIONS BY VISUALIZING FORCE FIELDS

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In tele-operating an UAV, human operators fully rely on cameras to control the vehicle from a distance. To increase operator situation awareness and reduce workload, haptic feedback on the control stick has been developed which acts as an automatic collision avoidance system. A virtual force field surrounding the moving vehicle interacts with obstacles surrounding it, yielding repulsive forces on the stick that lead the vehicle away from them. Albeit successful in significantly reducing the number of collisions, the haptic interface received low user acceptance ratings. Operators do not always fully understand the collision avoidance automation intentions, and they experience the haptic forces as intrusive. This paper discusses the development and testing of several visualizations of the underlying automation intentions, primarily the artificial force field. Results of a human-in-the-loop experiment show that these visualizations indeed led to higher user acceptance ratings, without affecting the operator's safety, performance and workload.

Operating UAVs can be a challenging task, especially beyond the operator's line of sight, where the drone is controlled by teleoperation. Locations with low visibility, e.g., due to the lack of light or because of obstructions like smoke, pose a threat to teleoperation since the on-board cameras and other electro-optical sensors cannot provide quality images. In addition, the teleoperator lacks multiple-sensory information of the surrounding environment (e.g., vehicle motion, vibrations, environment/vehicle sound and outside view) compared to pilots flying a manned aircraft. The information is usually provided by visual displays from on-board cameras and sensors which have limited resolution and Field of View (FOV) (Draper & Ruff, 2001).

To compensate for the lack of direct sensory input from the environment, a haptic interface has been developed for collision avoidance (Lam, Mulder & Van Paassen, 2007, 2008). A Haptic Collision Avoidance System (HCAS) uses an Artificial Force Field (AFF) to map environmental constraints to steering commands for avoiding collisions with objects.The resulting haptic feedback system provides information through the sense of force on the control device: a *shared* control system between human and automation. Research shows that these shared control systems are often not optimal, with low user acceptance ratings which are often caused by a lack of information of how the haptic system works, i.e., why are forces felt?, and where do these forces originate from? (Griffiths & Gillespie, 2005; Seppelt & Lee, 2007; Lam, Mulder & Van Paassen, 2007, 2008).

This paper presents two visual displays that can accompany the haptic feedback and that aim to provide some visual explanation of what the haptic feedback system's intentions are. Seppelt and Lee (2007) showed that these visualisations of the haptic feedback intentions can increase higher user acceptance ratings. The paper will first briefly discuss the principles of our haptic feedback systems, followed by the visualizations developed, and then describe the results of a first human-in-the-loop experiments to test our novel system.

Haptic Collision Avoidance System

Figure 1 illustrates the basic building blocks of the Haptic Collision Avoidance System developed by Lam, Mulder & Van Paassen (2007, 2008). The HCAS informs the operator if a certain control input will lead to a higher risk of an obstacle collision. To realize this function, the environment surrounding the UAV is evaluated by an obstacle detection algorithm. Detection is done by a Laser Imaging Detection And Ranging (LIDAR) sensor, which measures the object-UAV distance by analyzing the reflected light by the laser beam mounted below the UAV. The laser scans the environment in two dimensions, returning distance measurements at specific angle intervals. With this mapping, which resembles the visual control task of the pilot but extends it to all directions, the Artificial Force Field (AFF) computes the risk of collision. This risk is converted to a haptic force on the control stick, yielding a continuous haptic feedback that warns the operator of a potential collision.

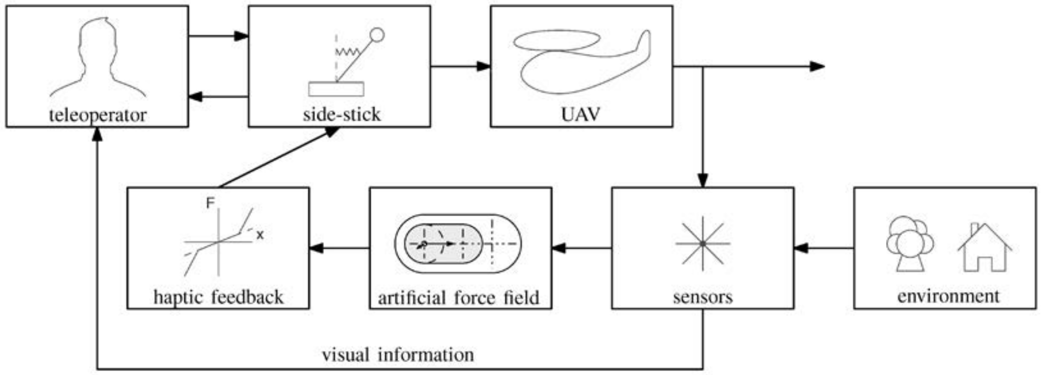


Figure 1: Schematic representation of haptic interface for UAV teleoperations.

The AFF used by Lam, Mulder & Van Paassen (2007, 2008) is programmed as a Parametric Risk Field (PRF), a "potential field" that extends outside the physical limits of the UAV being tele-operated and that shrinks and extends dependent on the direction of the UAV velocity. Figure 2 illustrates that all obstacles which fall into the potential field lead to repulsive forces; these are summed and averaged, yielding a single Final Avoidance Vector (FAV), with a direction and amplitude, equivalent to the force feedback on the operator's control manipulator.

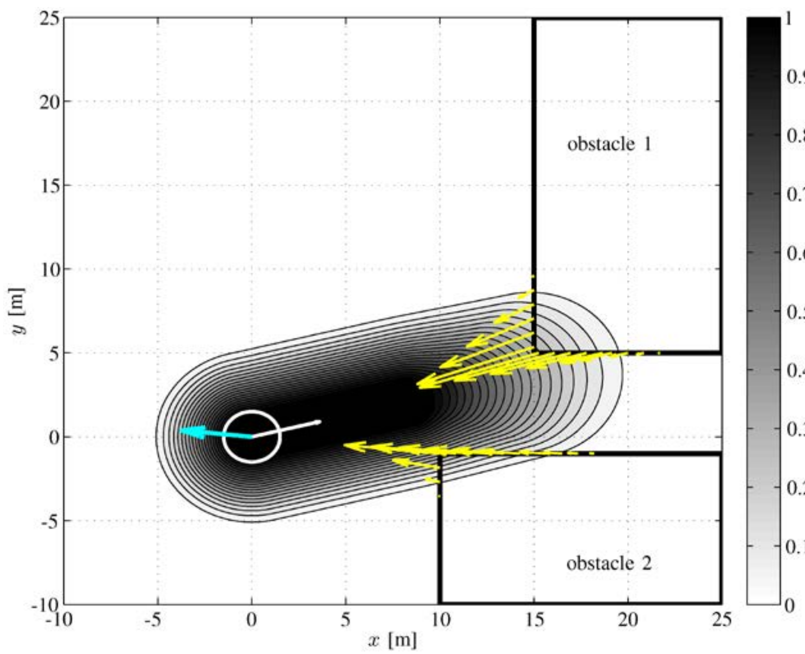


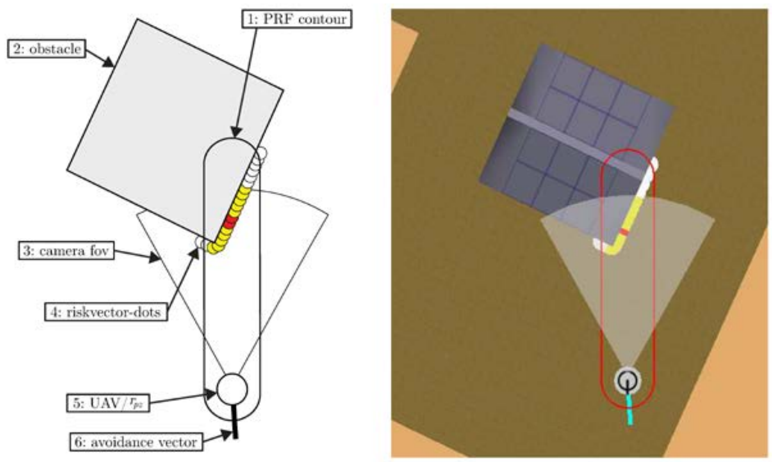
Figure 2 : Risk vectors (yellow, from the obstacles) and the FAV (blue vector extending from the UAV center).

Our previous research showed that our haptic feedback system significantly reduced the number of collisions and increased task performance, compared to a situation without haptic feedback. Subjective workload measured with NASA-TLX also increased with haptic feedback, especially the physical workload and subject frustration levels (Lam, Mulder & Van Paassen 2007, 2008). Subjects explained that at some moments the haptic feedback was 'too strong', and 'unpredictable', as subjects could not decipher what reasoning was underlying the HCAS feedback forces. In the next section we discuss two visualizations developed to mitigate this experience.

Haptic Feedback Visualizations

In our previous work, the UAV tele-operators had a (simulated) on-board forward-looking camera view display, as well as a two-dimensional ‘navigation display’, which presents a top-down bird’s eye view of the situation, including the UAV, the obstacles, and a triangular shape which showed the field-of-view of the forward-looking camera. To avoid clutter on the three-dimensional camera image, and since our AFF is currently still a two-dimensional, horizontal force field, two visualizations were developed to be added on the navigation display.

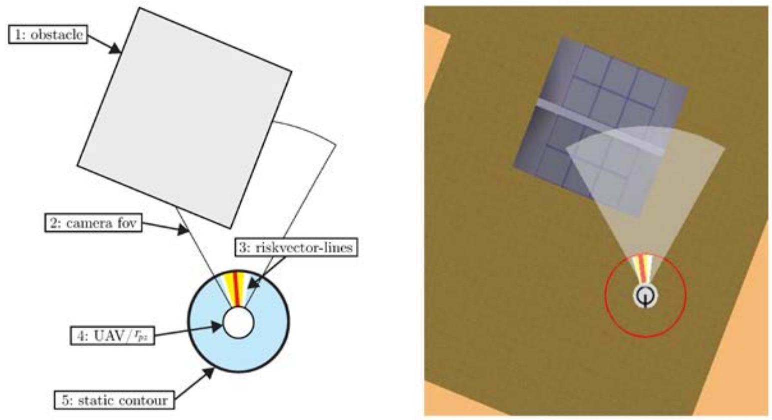
The PRF Contour Risk Field (PRF-CRF) is our first visualization, Figure 3. It is almost a 1:1 visualization of the virtual force field of Figure 2 on the navigation display. However, to reduce clutter, all information within the red outer contour is deleted, and all risk vectors are reduced to colored dots, color-coding how much risk they represent. White dots mean low-risk and barely feelable haptic feedback, yellow dots mean medium risk with noticeable feedback, and red dots mean maximum risk corresponding with maximum force feedback. The FAV is a vector line attached to the UAV center, which changes its length and direction perfectly corresponding with the haptic feedback force put to the control manipulator.



(a) PRF-CRF description (b) PRF-CRF during flight

Figure 3 : The PRF Contour Risk Field (PRF-CRF) visualization, developed to work together with the HCAS.

The Static Circular Risk Field (SCRF) is the second visualisation, Figure 4. In contrast to the first visualization, the SCRF does *not visually correspond to the HCAS algorithm.* Inspired by our previous research on supporting pilots in self-separation (Van Dam, Mulder & Van Paassen, 2008), only a circle is shown the size of which does not change (hence: static). Within the circle, white, yellow and red lines show the directions of risk vectors coming from obstacles with low/medium/high risk, respectively. In such a way, a 360 degree ‘risk map’ is shown within the circle, which we hypothesized to be easier to understand by teleoperators as compared to the PRF-CRF. Whereas the latter can shrink and extend rapidly, depending on the UAV’s velocity and acceleration, possibly overlapping the obstacles, the SCRF only presents the risk map within the fixed static circle, without much overlap.



(a) SCRF description (b) SCRF during flight

Figure 4 : The Static Circular Risk Field (SCRF) visualization developed to work together with the HCAS.

Experiment

We performed an experiment to test the usefulness of our haptic interface with the two novel visualisations. Our main interests were whether the participants could better understand, predict, and because of that would better appreciate our HCAS. The setup of the experiment was very similar to the experiments reported by Lam, Mulder & Van Paassen (2007, 2008) and will be only briefly explained in this section; for more details see our earlier work.

The experiment had 12 participants (all males, right-handed, average age 25 years) and was conducted in the fixed-base human-machine interaction simulator. Subjects controlled a simplified UAV helicopter in the horizontal plane only (altitude was fixed) using a side-stick. Two displays were presented: (i) a simulated on-board camera view (60 degrees field of view) was projected on a wall 3 meters in front of the subjects as an outside visual display; (ii) a navigation display was presented on an 18 inch LCD screen in the simulator cockpit (i.e., head-down).

Subjects were instructed to fly the UAV from waypoint to waypoint, visualized with smoke plumes, in an obstacle-filled urban environment containing multiple buildings and artefacts. The obstacle course was fixed, and was clearly shown on the two visual displays. Subjects were instructed to fly the course as fast as possible (low priority), as closely as possible to the waypoints (medium priority), while avoiding any collisions (highest priority). When a collision did occur, the simulator was frozen for 10 seconds, i.e., inflicting a time penalty, while a loud beeping sound was heard. After the penalty, the UAV was repositioned to a fixed starting point corresponding to the 'subtask' where the collision occured. Each obstacle course was constructed by randomly 'connecting' 6 different sub-tasks, similar to Lam, Mulder & Van Paassen (2007, 2008).

The experiment had two independent variables: the six subtasks and the HCAS display configuration. The latter had three levels: No Visualization (NV), and the novel PRF-CRF and SCRF visualizations. Objective dependent measures were related to safety (number of collisions), performance (total elapsed time per run), control activity (stick rate), haptic activity (haptic forces). Subjective dependent measures related to workload (NASA TLX) and operator acceptance (using the Controller Acceptance Rating Scale (CARS), Lee et al., 2001). In addition, we asked our subjects to complete a small questionnaire (focusing on acceptance and preference) after the experiment.

Results

Contrary to our hypotheses, neither of the two visualizations led to any significant changes, that is, improvements in safety and task performance were not found. Regarding safety, the number of collisions was very low, 26 in 108 runs; it increased from 7 (NV) to 10 (PRF-CRF) and 9 (SCRF). Most collisions (15) occured in subtask 4 which required subjects to control the UAV through a long, narrow corridor. The mean risk vector magnitude slightly decreased with the two visualizations, and the average minimum distance to obstacles increased, both not significantly; there was no dependency between subtasks. Considering task performance, there were no significant differences in the total elapsed time and average UAV velocity. None of the control activity metrics, neither any of the haptic feedback force metrics, changed significantly.

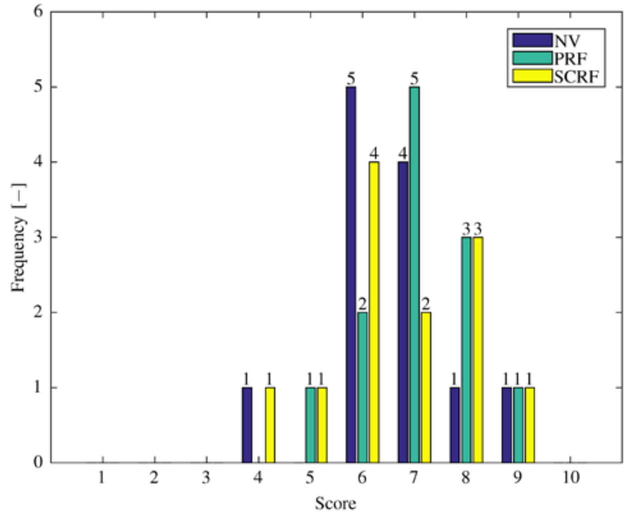


Figure 5 : Controller Acceptance Rating Scale (CARS) results (NV = No Visualization; PRF = PRF-CRF, and SCRF = Static Circle Risk Field).

When considering the subjective data, contrary to our hypothesis the subjective workload (TLX) did not reduce significantly with either of the two visualizations, which both led to slightly higher TLX frustration levels. Figure 5 shows that the CARS scores were slightly higher for the SCRF and PRF-CRF visualizations, as compared to the NV condition, an effect that was also not significant. The end-of-experiment questionnaire confirmed the CARS results, in that the PRF-CRF was preferred by most subjects in most conditions except for subtask 4 (see below). Subjects commented to use the PRF-CRF outer boundary to see when the haptic feedback would trigger and thus could make sharper turns, i.e., helping them to understandi the HCAS functioning and also improving the timing of their control actions.

Only in subtask 4 the SCRF was preferred. Here, while flying through the small corridor, the PRF-CRF visualization cluttered the screen with many risk vector dots, making it difficult to see how far the UAV was away from the walls. Occasionally, also a large drop in visual display update rate occurred with the PRF-CRF display because of drawing the many risk dots. Subjects commented also that in the PRF-CRF condition, showing the Final Avoidance Vector was not very useful; here, especially the outer contour mattered and was considered helpful.

The end-of-experiment questionnaire contained four questions where subjects had to rate their agreement to statements. When asked "*Did the visual feedback give you enough information about the workings of the haptic feedback?*", "*Have you felt any contradictions between the information received by the haptic feedback and the information shown on the display?*", the PRF-CRF scored significantly better than the SCRF, confirming our design aims with the former display which was to visualize 1:1 the virtual force field. When asked "*Did the visual feedback interfere with your flight performance compared to having no feedback?*", no differences between the two visualizations were found, and most subjects scored "low" on this interference. Finally, when asked "*Did you use the visual feedback to change your control strategy?*". The PRF-CRF scored significantly higher than the SCRF, and subjects reported that with the PRF-CRF they could fly closer to walls; yet, our other objective metrics did not provide any evidence that could possibly confirm this statement.

Conclusions

This research aimed to design and test two novel visualizations developed to obtain higher user acceptance ratings for a haptic feedback system in UAV tele-operation. Previous research showed that adding visualizations to haptic interfaces led to improved safety and operator performance. The human-in-the-loop experiment showed that our participants did not change their control strategies when either visualization was provided. Only marginal differences in objective dependent measures were found, and the new designs did neither significantly improve, nor deteriorate, the operator's safety, task performance and workload. Subjective data obtained through the CARS rating scale and the end-of-experiment questionnaire did show, however, that both visual displays were a welcome addition, as they provided more clarity of the internal functioning of the haptic feedback system, and helped increasing spatial awareness and timing of control actions. Differences were small, however, between conditions, and although the acceptance of the HCAS was increased, this increase was not significant. In our future work we will focus on using more subjects and developing experimental scenarios to better evaluate user acceptance and distringuish between the conditions with and without additional visualizations.

References

Draper, M.H., and Ruff, H.A. (2001). Multi-Sensory Displays and Visualization Techniques Supporting the Control of Unmanned Air Vehicle. *IEEE Int. Conf. Robot. Automation*: 1–6.

Lam, T.M., Mulder, M., and Van Paassen, M.M. (2007). Haptic Interface for UAV Collision Avoidance. *The International Journal of Aviation Psychology*, 17(2): 167–195.

Lam, T.M., Mulder, M., and Van Paassen, M.M. (2008). Haptic Feedback in UAV Tele-operation with Time Delay. *Journal of Guidance, Control & Dynamics*, 31(6): 1728–1739.

Griffiths, P.G., and Gillespie, R.B. (2005). Sharing Control Between Humans and Automation Using Haptic Interface: Primary and Secondary Task Performance Benefits. *Human Factors*, 47(3): 574–590.

Seppelt, B.D., and Lee, J.D. (2007). Making adaptive cruise control (ACC) limits visible. *Int. J. Hum. Comput. Studies*, 65(3): 192–205.

Van Dam, S.B.J. and Mulder, M. and Van Paassen, M.M. (2008). Ecological Interface Design of a Tactical Airborne Separation Assistance Tool. *IEEE Trans. on Systems, Man & Cybernetics, Part A*, 38(6): 1221–1233.

Lee, K. K., Kerns, K., Bone, R. and Nickelson, M. (2001). Development and Validation of the Controller Acceptance Rating Scale (CARS). *Proc. of the 4th USA/Europe Air Traffic Management R&D Seminar, Santa Fe (NM), December 7-13, paper 161*: 1-14.