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Increasing Acceptance of Haptic Feedback in UAV Teleoperation by Visualizing Force Fields

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***Abstract*—Haptic interfaces have been developed to assist human operators controlling unmanned aerial vehicles (UAV) beyond line-of-sight. These systems complement the predominantly camera-based visual interfaces and act like a collision-avoidance system: when nearing obstacles, the operator gets re-directed by the haptic force feedback. Previous research showed that, although being successful in reducing the number of collisions, these haptic interfaces also lead to lower user acceptance, as the operators do not always understand the system's intentions. This paper discusses two novel visualizations which were developed to increase operator acceptance. Both designs were evaluated in a human-in-the-loop experiment (n=12). Results from acceptance-related questionnaires show that our subjects preferred teleoperating the UAV with the visualizations active. Acceptance ratings were higher for the same levels of safety, performance and operator workload.**

I. Introduction

Teleoperating unmanned aerial vehicles can be a challenging task, and human factors issues are reported in 21% to 67% of all UAV-related accidents [1]. When operating beyond line-of-sight the operator depends on camera images only, with often limited resolution and field-of-view (FOV), and lacks the multiple-sensory information of the environment as compared to piloted vehicles (e.g., vehicle motion, vibrations, environment/vehicle sound and outside view) [2]–[4].

To compensate for the lack of direct sensory input from the environment, a haptic interface has been developed [4], [5]. It acts as a haptic collision avoidance system (HCAS) that uses an artificial force field (AFF) to map environmental constraints, such as obstacles, to steering commands to avoid collision with these obstacles [6], [7]. The HCAS-forces are put to the control manipulator which the operator uses, yielding a *shared control* system between human and automation [8], [9]. Evaluations of our haptic shared control systems revealed that, although successful in reducing the number of collisions, operators do not always appreciate them, resulting in low user acceptance ratings [4], [10].

Likely causes are that the operator does not understand the way the haptic system works: why do the forces appear, and what are the constraints that the system includes in generating the force feedback? These findings are in agreement with those reported by Seppelt & Lee [11] who developed a visual interface to complement their haptic driver assistance system. In this paper a similar approach is followed, and two visual displays will be discussed that can accompany the haptic feedback. Both aim to provide an intuitive visual explanation of the HCAS' intentions, and have been tested in a human-in-the-loop experiment. The current paper, which extends our previous publication on this topic [12], is structured as follows. We first briefly discuss the general concept of the HCAS, and then describe the two visualizations. The experiment and its results follow, and the paper ends with some conclusions and recommendations for future work.

II. Haptic Collision Avoidance System

A. System Architecture

Fig. 1 illustrates the general concept of the HCAS [4]. The teleoperator controls the UAV using a side-stick control manipulator. Based on on-board sensors (like radar or lidar) the environment is scanned for obstacles. An artificial force field is generated, surrounding the vehicle and moving with it, which can interact with the detected obstacles when the vehicle comes closer [7]. The gradient of the potential field then yields a repulsive force which can be added to the control manipulator, leading to a haptic force-feedback of environmental constraints to the operator.

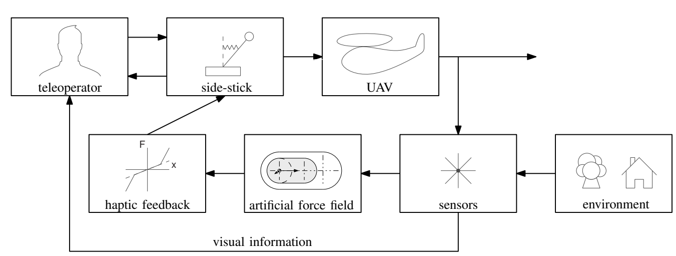


Fig. 1. Schematic representation of haptic interface for UAV teleoperation.

B. Artificial Force Field

The AFF moves with the vehicle and is used to map the environment constraints to forces on the stick by computing the gradient of the potential field. When considering UAV teleoperation in the horizontal plane only, the AFF can be constructed in many ways, such as the parametric risk field (PRF) illustrated in Fig. 2, discussed in detail in [7].

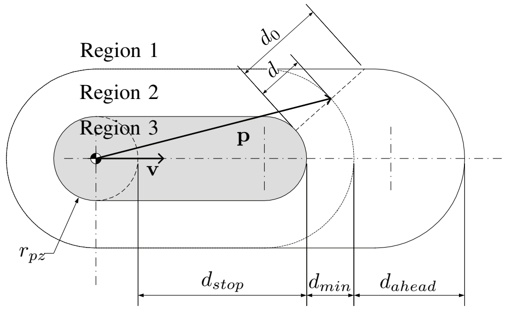


Fig. 2. Parameters for a Parametric Risk Field, with the inner and outer contour lines [7].

Around the UAV a "protected zone" is constructed which can extend in the direction of motion. The potential function is used to calculate the risk vectors as follows:

$$P(\mathbf{p}, \mathbf{v}) = \begin{cases} 0 & \text{if } \mathbf{p} \text{ in Region 1,} \\ \cos(\frac{d}{d_0}\frac{\pi}{2} + \frac{\pi}{2}) + 1 & \text{if } \mathbf{p} \text{ in Region 2,} \\ 1 & \text{if } \mathbf{p} \text{ in Region 3.} \end{cases} \quad (1)$$

Hence, the risk scales from 0 (no risk) to 1 (maximum risk) in a continuous fashion. With the potential field known, the final avoidance force vector (FAV) can be computed by taking the risk values generated by the PRF from all detected obstacles, and summing them up to one value, the FAV, which will then be used as the force feedback. This concept is illustrated in Fig. 3, in a two-obstacle scenario.

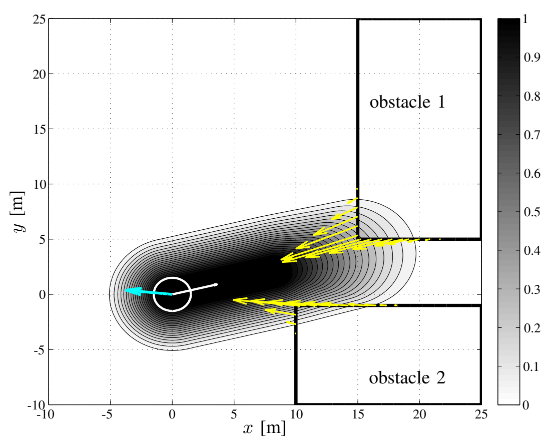


Fig. 3. Risk vectors (yellow, originating from the obstacles) and the final avoidance vector (blue, originating from the UAV center).

C. *Previous Experiments*

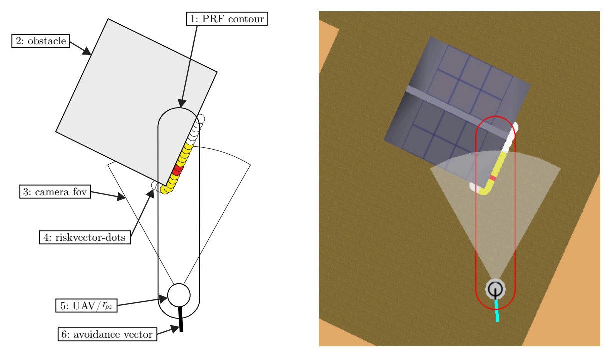
The HCAS has been extensively tested in several human-in-the-loop experiments [4], [5]. All experiments showed that indeed the number of collisions reduce significantly when haptic feedback is active. However, the subjective workload ratings were higher, as subjects reported an increase in their physical workload and frustration levels [4]. Subjects reported that sometimes the haptic feedback was 'too strong' or 'un-predictable', leading to lower user acceptance ratings. Later studies with the same set-up confirmed these findings [13].

III. HCAS Visualization Designs

Teleoperators using the haptic interface are assumed to control their UAV using two displays: a 'primary flight display' showing the image of a front-facing camera on-board the vehicle, and a top-down view of the UAV on a 'navigation display' (ND). Based on the results from [10], who showed that augmenting the primary flight display with haptic information easily gets cluttered, we decided to focus on the navigation display only. Two designs were constructed which both aim to provide visual information on how the parametric risk field AFF interacts with the obstacles in the environment to result in the haptic feedback forces felt in the control manipulator.

A. *Design 1: PRF Contour Risk Field*

A straightforward idea would be to reproduce the PRF directly on the display, but this idea was soon abandoned as it led to a heavily-cluttered ND. Rather, a slimmed-down version was created, the PRF Contour Risk Field (PRF-CRF), illustrated in Fig. 4.



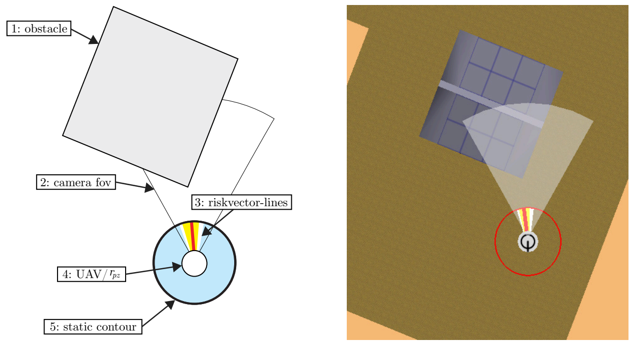
(a) PRF-CRF description (b) PRF-CRF during flight

Fig. 4. The PRF Contour Risk Field visualization (right), shown in a situation with one obstacle.

The basic ND shows the UAV from above, in a heading-up configuration, with a triangular shape representing the FOV of the forward-looking camera, and the near-by obstacles in the environment. The PRF-CRF overlay shows the *outer contour* of the PRF (see Fig. 2) in red, and all risk vectors of the AFF (see Fig. 3) reduced to small circles, color-coding the risk they represent. White dots represent low risk vectors which result in very small haptic feedback, yellow dots represent medium risk and noticeable feedback, red dots represent maximum risk leading to maximum force feedback. The final avoidance vector FAV is shown as a blue vector line attached to the UAV center, which changes its length and direction according to the magnitude and direction of the haptic feedback force.

B. *Design 2: Static Circular Risk Field*

A second design was considered which uses the same PRF and FAV computations, but which *does not visually correspond* with the PRF. This allowed us to investigate whether a resemblance between visual representation and underlying HCAS algorithms would make any difference in terms of user acceptance, performance and safety of UAV teleoperation. The Static Circular Risk Field (SCRF) is illustrated in Fig. 5, in a similar scenario as the PRF-CRF of Fig. 4.



(a) SCRF description (b) SCRF during flight

Fig. 5. Static Circular Risk Field in a one obstacle scenario.

The SCRF is inspired by our research on supporting pilots in self-separation, see [14], and only shows a circle with a fixed size (hence: static). Within the circle, white, yellow and red lines indicate the risk vectors coming from obstacles with low/medium/high risk, respectively, yielding a 360 degrees 'risk map', reducing clutter. The SCRF was hypothesized to be easier to comprehend as compared to the PRF-CRF, which can shrink and extend rapidly depending on the UAV's velocity and acceleration, whereas with the SCRF pilots simply had to 'avoid flying in the direction of the risks'. Another difference with the PRF-CRF was that with the SCRF the FAV vector is not shown, rather, it is replaced by a red line within the circle representing the highest risk, see Fig. 5.

Table I summarizes the two visual designs.

TABLE I
ELEMENTS OF PRF-CRF AND SCRF.

Element	**PRF-CRF**	**SCRF**
PRF Algorithm	Only outer contour visible	*Not visible*
Risk Vectors	On obstacle, by colored dots	On risk map around UAV, by colored risk lines
FAV	Blue vector line attached on UAV	*Not visible*
Highest Risk	*Not visible*	Red vector line on the risk map

IV. HUMAN-IN-THE-LOOP EXPERIMENT

A human-in-the-loop experiment was conducted to investigate the effects of the two visualizations on user-acceptance of the haptic interface. Its setup was very similar to our previous research [4], [5], and will only be briefly explained here.

A. METHOD

1) Participants: Twelve male TU Delft students (avg. 25 yrs) participated, all right-handed. Their consent was obtained; they received no monetary compensation.

2) Apparatus: Subjects were seated in a fixed-base simulator and controlled a simulated UAV helicopter using an electro-hydraulic side-stick mounted to their right-hand side. Two displays were presented: (i) a simulated on-board forward-looking camera (FOV 60×45 degrees) was projected on a wall 3 meters in front of the subjects, and (ii) a navigation display was presented in the cockpit on an 18 inch LCD screen.

3) UAV Model: A control-augmented UAV helicopter model was simulated which could be easily controlled [4]. A for/aft longitudinal stick deflection resulted in a forward/backward *velocity* command; a left/right lateral stick deflection yielded a left/right turn *rate* command (max. 0.32 rad/s). The maximum velocity was 5 m/s, maximum acceleration 1 m/s^2, and maximum turn acceleration was 2 rad/s^2. The UAV altitude was automatically kept constant.

4) Instructions: Subjects were instructed to fly the UAV along an obstacle course, from waypoint to waypoint (visualized by smoke plumes), in an urban environment containing multiple buildings and artefacts. The obstacle course was fixed and shown on both displays. Subjects were instructed to fly along the course as fast as possible (low priority), as closely as possible to the waypoints (medium priority), while avoiding collisions (high priority). When a collision did occur, a time penalty was given: the simulation was frozen for 10 seconds and a loud beeping sound was played. After the penalty, the UAV position would reset to the nearest default starting position, and the simulation resumed.

5) Obstacle Courses: An obstacle course consisted of six different subtasks, presented in a randomized order. Each subtask required a particular manoeuvre, to force pilots to vary the control strategies used. The waypoints were shown as smoke plumes (on the outside visual display only) to measure both the flight performance and also to reduce the visibility around the obstacles. The six subtasks, illustrated in Fig. 6, were connected in a different order such that three separate and distinct obstacle trajectories were obtained.

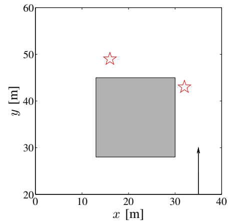
6) Independent Variables: The experiment had two independent variables: (i) the three HCAS displays: No Visualization (NV), the PRF-CRF, and the SCRF visualization, and (ii) the six subtasks introduced above. These were not tested in a factorial fashion. Rather, for each of the three HCAS visualizations three different trajectories were run (which each contained all six subtasks) randomized using a Latin Square.

The haptic feedback was kept constant, and was set to the 'Relax Task' setting as recommended by [13].

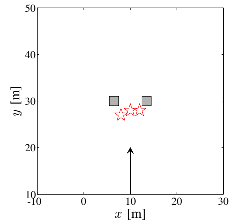
7) Dependent Measures: Objective dependent measures were related to safety (e.g., number of collisions, minimum distance to obstacles), performance (e.g., total elapsed time per run, average velocity, distance to waypoints) and control and haptic activity (not elaborated here any further).

Subjective measures were obtained using questionnaires. After each run we measured workload using the NASA-TLX [15], and user-acceptance using the controller acceptance rating scale (CARS) [16]. When all runs were completed, a final questionnaire was issued which contained various questions focusing on user acceptance and preferences.

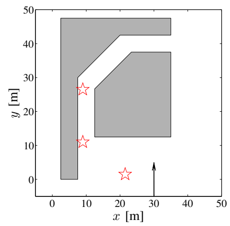
8) Statistical analyses: Statistical analyses were done using a repeated-measures ANOVA ($\alpha = 0.05$); significant results were further evaluated with post-hoc tests, pairwise Bonferroni and Greenhouse-Geisser corrections were applied to the data. Measures with ordinal variables were tested with a non-



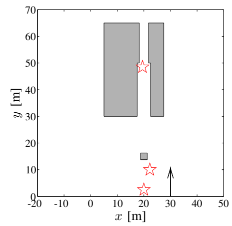
(a) Subtask 1



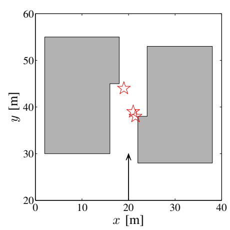
(b) Subtask 2



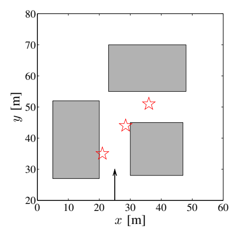
(c) Subtask 3



(d) Subtask 4



(e) Subtask 5



(f) Subtask 6

Fig. 6. The six subtasks of this experiment. In these figures, the stars show the waypoints, the arrows show the default starting points (arrow origin) and required UAV flight direction (arrow point).

parametric Friedman test, with Wilcoxon matched signed rank for post-hoc analysis, or a Kruskal-Wallis test with Mann-Whitney post-hoc. Runs where a collision occurred were excluded from the analysis, except for the collision count measure. For each participant the dependent measures of multiple runs of the same subtask were averaged.

B. Hypotheses

First, we hypothesized that, when compared to the haptics-only condition (NV) both our visualizations (PRF-CRF and SCRF) would help operators to improve their performance, increase the overall safety of operation, and reduce operator workload (H.I). Second, we hypothesized that the novel visualizations would also lead to a higher user acceptance of the HCAS, with a preference for the display that showed the HCAS function in a 1:1 fashion, the PRF-CRF (H.II).

V. Results

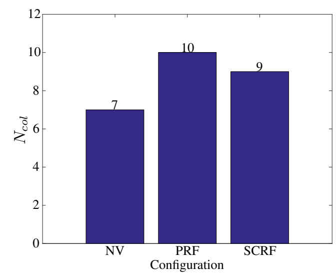
In this section some of the main results of the experiment will be discussed. In many figures the data are shown as a function of the visual display (three levels), averaged over all subtasks, and also for each individual subtask.

A. Objective measures

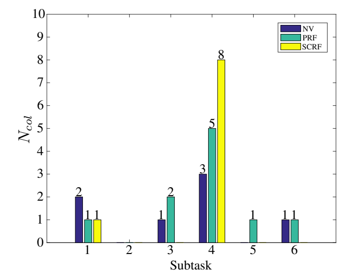
1) Safety: Fig. 7 shows the number of collisions for each of the three visualizations (i.e., summed-up for each subtask) and six subtasks (right). The number of collisions increased slightly when the visual overlays (PRF-CRF (+3) and SCRF (+2)) were active (not significant), which appears to happen especially in subtask 4. This subtask led to a significantly higher number of collisions (16 of the total 26) and was also reported by our subjects to be the most difficult task. It required them to fly through very narrow corridor, where the haptic forces sometimes cancelled-out each other.

The total number of collisions, 26 in a total of 108 runs, is comparable with previous research of [4] (40 runs, 8 collisions) and [13] (180 runs, 24 collisions). Note that their subtasks 3 and 4 were not the same as those simulated here, so comparisons should be done with care.

Other safety-related measures showed slight benefits (all not significant) of the two visualizations: the mean risk vector decreases, the average minimum distance to obstacles increases.



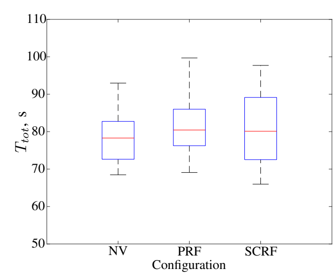
(a) Visual display



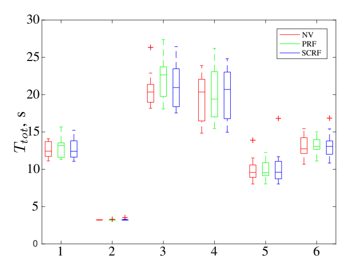
(b) Subtask-specific

Fig. 7. Number of collisions.

2) Performance: Fig. 8 shows the averaged total elapsed time of each run, for each of the three displays (averaged over subtask) and for each subtask. There were no significant differences between conditions, except that subtask 2 was done significantly faster. Other performance measures, such as the distance-to-waypoints and average velocity of the UAV, did also not lead to any observable trends or differences.



(a) Visual Display

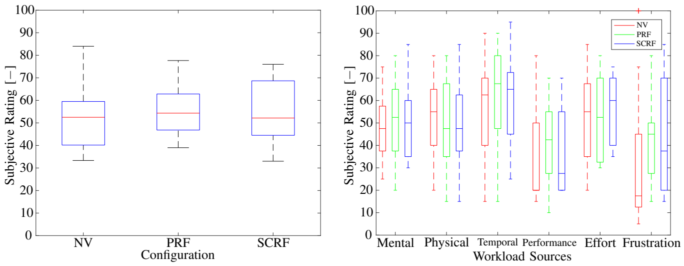


(b) Subtask-specific

Fig. 8. Time elapsed.

B. Subjective Measures

1) Workload: Fig. 9 shows the results of the NASA-TLX workload rating, and its sub-scores (right), for the three visualizations only (as the TLX rating was given after each run, and not after each subtask within a run). There is no observable difference in the overall workload, but the subscores show slighly lower 'Physical' source to workload, at the cost of a slightly higher 'frustration' source to workload. None of these effects were statistically significant, however.



(a) Overall rating (b) Rating for specific sources

Fig. 9. NASA TLX workload scores.

2) CARS ratings: Fig. 10 shows that the CARS scores were higher for the SCRF and especially the PRF-CRF visualization, as compared to the NV condition, an effect that was not significant, however.

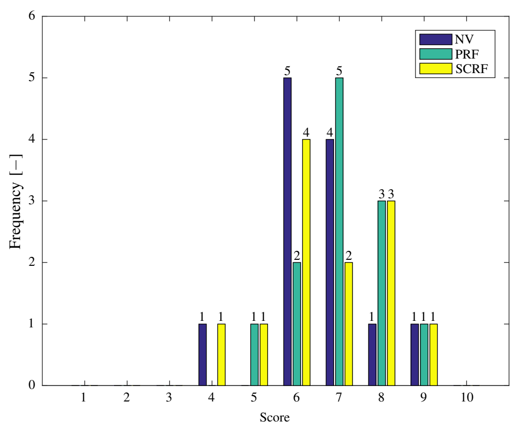
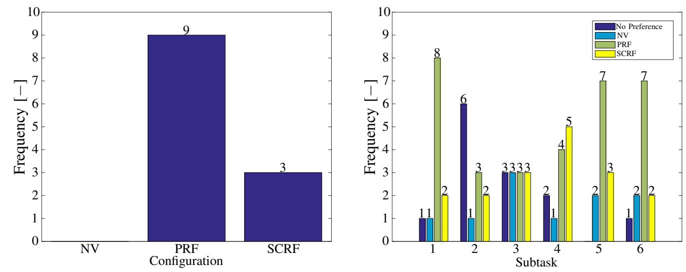


Fig. 10. CARS results.

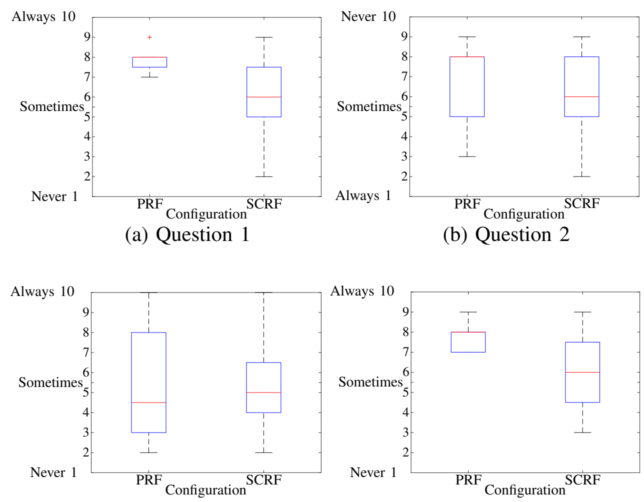
3) End-of-experiment questionnaire: Fig. 11 shows the visual display (NV, PRF-CRF or SCRF) which the subjects preferred overall, and per sub-task (right). We see that the data confirm the CARS findings, in that the PRF-CRF was preferred by most subjects (9 of 12) over the SCRF, except for subtask 4. Subjects commented that the PRF-CRF visualization's of the AFF outer contour was very helpful for them to see when the haptic feedback would trigger, which assisted them in making sharper turns. In subtask 4, when flying through a narrow corridor, the PRF-CRF visualization cluttered the display as it showed many risk vector dots, making it difficult to see how far the UAV was away from the walls. In addition, because so many dots were drawn with the PRF-CRF, occasionally the visual display update rate dropped significantly, which hampered UAV control.

The questionnaire also contained four questions which asked subjects to rate their answer on a scale from 1 to 10; results are shown in Fig. 12. When asked "*Did the visual feedback give you enough information about the workings of the haptic feedback?*" (Question 1), and "*Have you felt any contradictions between the information received by the haptic feedback and the information shown on the display?*" (Question 2), the PRF-CRF scored significantly better than the SCRF. Regarding Question 3, "*Did the visual feedback interfere with your flight performance compared to having no visuals?*", mixed results were found. Regarding Question 4, "*Did you use the visual feedback to alter your control strategy?*", our subjects indicated that with the PRF-CRF they mostly did (more on that below), whereas with the SCRF they only changed their strategy sometimes.



(a) Visual Display (b) Subtask-specific

Fig. 11. Preferred configuration from questionnaire.



(a) Question 1 (b) Question 2

(c) Question 3 (d) Question 4

Fig. 12. Questions 1-4 from questionnaire.

Finally, participants were asked which elements of the two overlays they liked and disliked; also other comments could be given. Showing the FAV on the PRF-CRF was reported to be not very useful: as the haptic feedback already provided the direction of the FAV, visualizing it was considered redundant. Most participants preferred the PRF-CRF especially in situations where the on-board camera did not provide enough information because of its limited FOV. The outer contour shown in the PRF-CRF provided useful information on the relative distance between the UAV and the obstacle, and allowed subjects to change their control strategy in a beneficial way as compared to the other conditions.

VI. Discussion

Previous research showed that adding visualizations to haptic interfaces led to improved safety and performance [10], [11]. The results of our experiment do not support this finding. Although some small beneficial trends in performance and safety-related measures appear, none of these are significant. Our visualizations had no effect on operator performance, and even led to a slight increase in the number of collisions. Workload ratings for all conditions were very similar and again no significant differences were found. Hence, we *reject our first hypothesis* (H.I), and conclude that the two visual overlays did neither significantly improve, nor deteriorate, the safety and performance of operation, and did not reduce workload.

Studying the safety-related measures reveals that especially in subtask 4, with a tightly-spaced, narrow corridor, the number of collisions was higher. Here, because of the geometric symmetry of the situation and the UAV motion parallel to two opposite walls, the haptic forces cancelled out, and the clutter caused by our visual overlays obscured the situation, deteriorating performance and leading to higher operator frustration levels. On the other hand, our visuals did help to (slightly) reduce the physical workload experienced by our subjects, which is often considered the main contributor to the higher workload ratings with haptics [4], [13].

Interestingly, in subtasks 1, 5 and 6 the participants had more space to maneuver, and both visualizations helped them to either to fly closer or remain further away from the obstacles, leading to a larger spread in data points as compared to the haptics-only condition. This hampers statistical analyses, but considering these more open environments may be more relevant and ecologically-valid than the current experimental setup. Also, especially in these subtasks our visual overlays were appreciated the most, see Fig. 11.

The subjective measures showed more interesting and also significant differences. The user acceptance rating (CARS) showed a higher acceptance for our two overlays (not significant), and most of our subjects (9 of 12) generally preferred the overlay that showed a 1:1 representation of the HCAS, the PRF-CRF. The latter interface also led to significantly better scores for questions related to whether the visual overlays helped to clarify the internal functioning of the haptic feedback system. These results lead us to *accept our second hypothesis* (H.II), which stated that the visuals would lead to higher user acceptance ratings. This acceptance is with caution, however since the effects are small.

A first recommendation would be to increase the number of participants, as using twelve participants led to loosely-spread data points. Doubling the number of participants could be enough to eliminate this uncertainty: using a 'small effect size' of 0.10, then 24 subjects would increase power from 0.61 to 0.91. Second, scenarios could be conceived that would allow subjects to more freely move in the virtual world, rather than following a fixed route. This could encourage them to apply different control strategies such that the potential benefits or issues with our interfaces would become more clear.

VII. Conclusions

This paper discussed two novel visualizations which were designed to obtain higher user acceptance ratings for a haptic collision avoidance system. Experiment results show marginal differences in the safety, performance, and workload related measures. Subjective measures, obtained through rating scales and a questionnaire, show that both visualizations helped our subjects to better understand the haptic forces, and were rated higher than the haptics-only condition. Especially showing the 'outer contour' of the artificial risk field was helpful. Subjects could better anticipate the haptic feedback and time their control actions. Future work focuses on improving the visualizations, and develop experimental scenarios that would help us to better evaluate (differences in) user acceptance.

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