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Experimental Comparison of Direct and Indirect Haptic Aids in Support of Obstacle Avoidance for Remotely Piloted Vehicles

Samantha M.C. Alaimo[1, 2], Lorenzo Pollini[1], Mario Innocenti[1], Jean Pierre Bresciani[2] and Heinrich H. Bülthoff[2, 3]

1. Dept. of Electrical and Computer Engineering, University of Pisa, Pisa 56126, Italy

2. Max Planck Institute for Biological Cybernetics, Tübingen 72076, Germany

3. Dept. of Brain and Cognitive Engineering, Korea University, Seoul 136701, Korea

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Abstract: The sense of telepresence is known to be essential in teleoperation environments, where the operator is physically separated from the vehicle. Usually only a visual feedback is provided, but it has been shown that by extending the visual interface with haptic feedback, that is complementing the visual information through the sense of touch, the teleoperator has a better perception of information from the remote environment and its constraints. This paper focuses on a novel concept of haptic cueing for an airborne obstacle avoidance task; the novel cueing algorithm was designed to appear "natural" to the operator, and to improve the human-machine interface without directly acting on the actual aircraft commands. Two different haptic aiding concepts for obstacle avoidance support are presented: an existing and widely used system, belonging to what we called the Direct Haptic Aid (DHA) approach class, and a novel one based on the Indirect Haptic Aid (IHA) approach class. Tests with human operators show that a net improvement in terms of performance (i.e., the number of collisions) is provided by employing the IHA haptic cue as compared to both the DHA haptic cue and/or the visual cues only. The results clearly show that the IHA philosophy is a valid alternative to the other commonly used approaches, which fall in the DHA category.

Key words: Haptic interfaces, teleoperation, remotely piloted vehicles, human-machine interface, obstacle avoidance, unmanned aerial systems.

1. Introduction

The aim of this work is the investigation of a novel haptic aid for remotely operated systems. Only visual cues are usually used in the context of remotely operated systems, however the adoption of an artificial feel system for the stick appears a viable approach capable of increasing the pilot/operator situational awareness, especially in terms of external disturbances, faults and environmental constraints, which degrade the vehicle maneuvering capability and the safety of the operation; this is extremely relevant for Unmanned Aerial Vehicles (UAVs) that might be operated far beyond the line of sight with relevant communication delays as well. Tactile cues have already been shown to successfully complement visual information, provided for instance by the displays of a remote Control Ground Station [1-2], and to improve efficiency and realism of teleoperation environments [3-4]. This paper focuses on the investigation of a haptic aid system, for an airborne obstacle avoidance task, extending what is already present in the literature, and exploits the concept of Indirect Haptic Aid [5-6]. Haptic cues in support of collision avoidance have already been investigated in the past, and have been heuristically defined as repulsive forces created by objects in the

Corresponding author: Samantha M.C. Alaimo, Ph.D., research fields: haptics, human-machine interface. E-mail: samanthaalaimo@yahoo.it.

environment in order to help the operator to avoid them. Research on autonomous mobile robots often presents virtual repulsive forces to avoid collisions with obstacles [1-2, 7-13]. The class of all Haptic aids, which produce forces and/or sensations (due to stick stiffness changes for instance) aimed at “forcing” or “facilitating” the pilot to take some actions instead of others is commonly called Direct Haptic Aiding (DHA) [6]. In the DHA structure, the operator must be compliant with the force felt on the stick. The sense of touch could be used instead, as originally intended in Haptic research, to provide the pilot with an additional source of information that would help him/her indirectly on the remote environment and leaving him/her the full authority to make control decisions. An haptic support system built upon this paradigm belongs to a class complementary to the direct haptic aiding, thus the name Indirect Haptic Aid (IHA) [5-6, 14]. As described later in the experiments, it often happens that the operator, while performing a task, has the natural tendency to oppose the force felt on the haptic device. Furthermore, when a haptic input requires a reaction in opposition to a stimulus rather than compliance, it creates a more ‘natural’ response by the human because it exploits the highly automatic and fast stretch response [15-17]. To the authors’ knowledge, the only other work using IHA [17] deals with path following for a manned aircraft, not with teleoperation issues, nor with obstacle avoidance. In Ref. [17], the authors suggest using the haptic device similarly to the flight director: the operator’s task is not to align a bar with a reference mark, but to bring the control stick in the centre to have the aircraft fly in the desired direction. In fact, the haptic device moves, in terms of neutral point shifting, in the opposite direction with respect to the one required by the target path and about a quantity proportional to the future error with respect to the path to follow. The IHA and DHA approaches were also compared against in a disturbance rejection task [5, 18]. There are several important issues in teleoperation, such as the analysis of the effects of communication delays [2, 19-20], which for the purposes of this paper we assume negligible. Another relevant problem and subject of active research is the modification and/or adaptation of the pilot behaviour in response to haptic stimuli [21-22]. This paper focuses on how to correctly design a haptic support system for obstacle avoidance [1, 11, 23]. We present and compare two different Haptic aiding concepts: an existing and widely used approach, belonging to the DHA approach class, and a novel one based on the IHA approach class.

The paper is organized as follows: Section 2 describes the simulation environment used for the tests; section 3 introduces the direct and indirect haptic aid approaches; section 4 describes the procedure used to tune the haptic feedback laws; sections 5 and 6 present the experimental results and the conclusions.

2. Simulation Environment

A simulated flight experiment was set-up with the mathematical model of a generic unmanned aircraft. A complete nonlinear aircraft model without stability augmentation, or autopilots was used [24-25] for the initial tests; these preliminary tests showed that pilots found the combination of obstacle avoidance with the necessary maneuvers and control actions to maintain altitude and speed too difficult. The aircraft model was therefore linearized about straight level flight, and a turn coordinator, and an altitude hold autopilot were added to the model. This allowed test pilots to concentrate on lateral maneuvers only, producing flight data leading to a reliable post-analysis of performance. The control stick was simulated by using a high precision force feedback device (omega.3, Force Dimension, Switzerland), which provided a simulated force up to 12 N. A virtual environment (See Fig. 1) was displayed during the experiments to produce the visual cues; a subjective view from the aircraft cockpit was simulated using a realistic synthetic environment created using the DynaWORLDS [26] software package. The environment consisted in a ground plane, the sky and buildings with regularly spaced windows to reproduce an appropriate perception of depth. The pilot task is to fly the aircraft in this urban canyon, that presents non-aligned buildings (non-Manhattan-like), and to arrive at the end of the road with a minimal number of collisions. As anticipated, in order to limit pilot workload and possible errors not connected with avoiding the obstacles, only the aircraft lateral-directional dynamics (i.e., roll and heading angles and lateral position) were controlled by the pilot. The aircraft velocity was kept constant (about 50 m/s).

An obstacle-generated force field was set-up. The purpose of the force on the stick is to aid the pilot in avoiding obstacles. It is common practice, in mobile robots research, to design repulsive fields, mimicking the force fields produced by charged particles or magnetic fields, that, originating from the obstacles, generate deviating forces [7]; although actual forces exerted by electro-static or magnetic interaction is inversely proportional to squared distance [27-28], it is more convenient, for both analysis and synthesis of haptic aids, to use a force field that varies its intensity linearly with distance [23].

Following this approach, we defined a repulsive force field around the obstacles: Each obstacle produces a radial force field (originating from its center); the intensity of the force field decreases with distance from the obstacle border and becomes zero beyond a certain threshold distance; then the vector sum of the force field generated by each single obstacle is used to generate a total force field. This force should not be confused with the actual force on the stick; but is used as a "distance sensor" to produce the two different haptic sensations that will be described in sections 3 and 4. More details on the actual implementation of the force field used in this paper can be found in Refs. [18, 20, 23].

The force field approach was found particularly valuable in our scenario because the cumulative force field defines a sort of "haptic tunnel" in between the obstacles, as shown Fig. 2, which portraits an example of the force field with force vectors and iso-intensity contour lines. Value and direction of the force field at the current position of the aircraft are used in the simulator to generate the haptic feel. In both DHA and IHA approaches, the force field shows a maximum intensity on the obstacle boundary decreasing with distance from it. The force field inside the obstacle is not relevant.

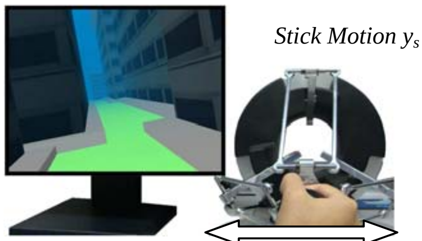

Fig. 1 The experimental setup: a sample out of the window view of the scenario, and the haptic device.

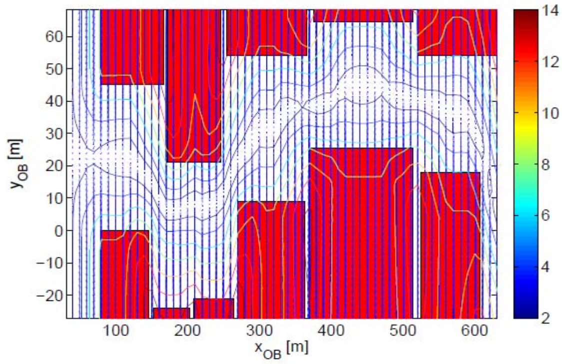

Fig. 2 Sample obstacles-generated force field (the color of contour lines codes the field strength in N).

3. Haptic Force Generation

It is well known that the stick must show certain stiffness and damping to the pilot, who otherwise tends to overshoot its goal position and has troubles finding the neutral point [5, 9-10]. Thus, a combination of two constant stiffness and damping terms (spring-damper system) and an external force, to be defined by the haptic aid algorithm, were employed. Since only the lateral aircraft dynamics were employed in the tests, only the lateral (along the Omega Device *y* axis) stick motions were allowed. Given the lateral stick displacement and velocity (y_S and $\dot{y}_S$), the force F_S felt by the operator during the obstacle avoidance task along the Omega Device *y* axis is

$$F_S = K_{el} y_S + K_d \cdot \dot{y}_S + F_E = F_{el} + F_d + F_E \quad (1)$$

where $F_{el}(K_{el} \cdot y_S)$ is the elastic term with constant stiffness K_{el}, $F_d(K_d \cdot \dot{y}_S)$ is the damping term, with a damping constant K_d, and F_E is the external force component. The first two terms are kept the same in all the three conditions of the experiments. The third one instead represents the actual haptic aid that is object of this study. Three types of external force F_E were compared in the presented experiment: DHA, IHA and a baseline force condition (No External Force, NoEF) in which $F_E = 0$. The goal of this experiment is to verify if and how an improvement of the operator's performance can be achieved by adding the haptic cues with respect to the condition in which only visual feedback is provided (NoEF condition).

3.1 Direct Haptic Aid Force Generation

The motivating idea of the DHA force is taken from previous works in which haptic cues supported collision avoidance [1]. Usually, in these types of applications, the haptic aid has always been implemented by transforming the repulsive forces created by the obstacles of the environment into a haptic force that deflects the stick in the direction of maneuvering away from the obstacles. Examples on autonomous ground mobile robots research usually involve virtual repulsive forces to avoid collisions with obstacles [1-2, 7-13]. These can be all classified as DHA approaches since, when the mobile robot is next to the obstacles, the haptic force helps directly the human operator by deflecting the stick in the direction needed for the avoidance maneuver. By following this principle, the repulsive force field associated with the obstacles and sampled at the aircraft position F_{OBS}, was used, appropriately scaled, to produce the haptic force on the stick; the sign of the haptic feedback was selected so that the haptic force would produce a stick deflection in the direction of obstacle avoidance:

$$F_E^{DHA} = \gamma \cdot F_{OBS,Y} \quad (2)$$

where $F_{OBS,y}$ is the lateral component of the force field and γ is an appropriate gain. When the distance is below a certain threshold (set to 50 meters in our experiments) a "repulsive force" is generated into the haptic device in order to let the aircraft make a turn in the direction opposite to the obstacle. Fig. 3 shows a simplified block diagram of the DHA simulator, where, F_E is the haptic force, F_h is the force exerted by the human operator who receives both the proprioceptive and visual feedback, and $F = F_E + F_h$ is the total forces exerted on the control device. If the pilot leaves the stick during the flight, the haptic force is sufficient to deflect the stick and maneuver away from the obstacle; the contribution of the pilot is needed though in order to farther increase the distance from the obstacle.

3.2 Indirect Haptic Aid Force Generation

The idea behind the first IHA force feedback proposed by the authors for UAV teleoperation [5] was to reproduce the sensations a pilot may experience inside a cockpit, and his/her reactions to motion cues (specifically wind gusts in that particular work). The aim was to increase the pilot situational awareness, by measuring relevant aircraft dynamic variables like angle of attack and load factor, and by reproducing them artificially via the haptic device; this approach turned out to be a valid aid for wind gust rejection during an altitude hold task [5]. Although the haptic force was not designed specifically to help the pilot in rejecting wind gusts, it successfully increased his situational awareness in terms of external disturbances since mean performance was improved with respect to the case of no haptic aiding (reduction of reaction time, for instance). Unfortunately, the design of an IHA-inspired obstacle avoidance aid appears complex since no force sensation is "naturally" generated by coming close to an obstacle, nor "real" stick sensation

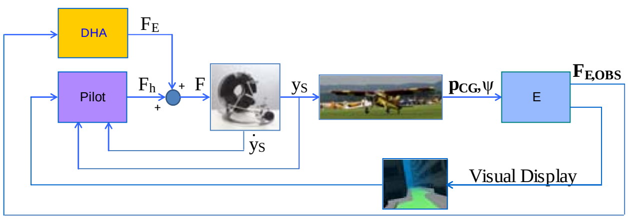

Fig. 3 DHA simulator scheme.

can be associated with the obstacle proximity. An IHA artificial feedback on the stick was therefore created using the artificial force field generated by the obstacles, as a function of obstacle proximity, which produced a disturbance-like sensation to be counteracted by the pilot. Using the concept described in Ref. [5], that opposition to haptic stimuli may be a ”more natural” pilot reaction with respect to compliance to stick motion, a haptic aid of opposite sign with respect to the DHA was designed:

$$F_E^{IHA} = -F_E^{DHA} \tag{3}$$

Direct application of Eq. (3) would result in a tendency to fly towards the obstacle instead of flying away from it as in DHA. In order not to penalize the expected IHA system performance, and to make it safe, the indirect force feedback F_E^{IHA} was complemented by a shift of the neutral point of the stick. The goal was to have the stick, de facto, move towards the obstacle, but without producing the aircraft to fly against it. For example, if an obstacle is on the right side, the stick would move to the right but, if the pilot is not in the loop, that is the pilot is not touching the stick, then the UAV will continue to fly straight. Notice that, with the DHA approach, in this case, the stick motion would induce the aircraft to fly away from the obstacle. In accordance with Ref. [16], if the pilot were to touch the stick, as in the normal situation, when the stick moves unexpectedly in one direction, it would be more natural for the pilot to move it to the opposite side. Going back to the example: with the obstacle on the right, when the neutral point of the stick shifts to the right, the pilot would feel this movement and he/she would naturally oppose it by moving the stick toward the left (that is, would move the stick a little back to the center) performing a turn to the left and actually fly away from the obstacle. The vanishing of the haptic cue would later inform the pilot that the obstacle is far away and not dangerous anymore. In other words, the IHA for obstacle avoidance follows the general concept of providing the pilot with the information about the presence of the obstacle on one side of the aircraft. This helps advising that in the remote environment a collision is going to happen and leaving him/her the full authority to take control decisions by changing the direction of the motion of the vehicle. Fig. 4 shows the employed IHA simulation scheme. This haptic aid was named Obstacle Avoidance Feel (OAF).

In order to modify the neutral point so that the haptic force F_E would produce no actual change of the aircraft trajectory (i.e., the aircraft continues to fly straight if the pilot takes no actions: $F_h = 0$), the aid force F_E, is sent to both the real Omega Device and a numerical model of it (the OD_i block in Fig. 4):

$$y_E = OD_i(s) \cdot F_E \tag{4}$$

The output y_E of the simulated model of the Omega Device is then subtracted from the total displacement of the end-effector of the real device. Given the total force on the stick F and the actual command to the aircraft y_A:

$$\begin{cases} F_h + F_E = F \\ y_S - y_E = y_A \end{cases} \tag{5}$$

The net result is that the operator moves the end-effector by y_A through the application of the force F_h. As a matter of fact, from Fig. 4 and Eq. (4), and assuming perfect modeling of the control device, that is $OD_i(s) = OD(s)$, we obtain

$$y_S = OD(s)(F_h + F_E) = OD(s) \cdot F_h + y_E \tag{6}$$

The actual aircraft command becomes

$$y_A = y_S - y_E = OD(s) \cdot F_h \tag{7}$$

The final result is that the F_E changes just the neutral point of the Omega Device by y_E and the only input to the aircraft dynamics is y_A from Eq. (7). Note that aircraft input $y_A = 0$ if the human force $F_h = 0$ although

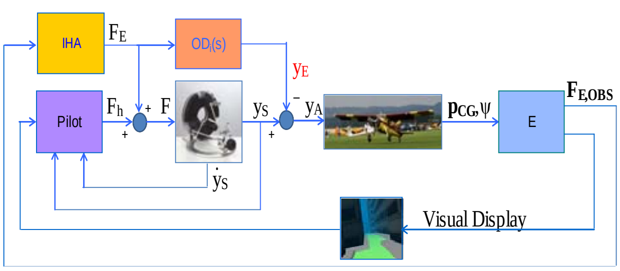

Fig. 4 IHA simulator scheme.

the stick was moved by the effect of F_E. The transfer function $OD_i(s)$ of the actual Haptic device used in the experiments was identified by using frequency sweeps (from 0.0262 to 10 Hz) and the Empirical Transfer Function Estimate (ETFE) technique [29]:

$$OD_i(s) = \frac{7.118}{s^2 + 26.76s + 864.8} \tag{8}$$

The goal of this research is to show that the IHA approach, which, roughly speaking, produces haptic sensations of opposite sign with respect to DHA case, can provide enough richness of information to the pilot and help him to avoid obstacles even without affecting directly aircraft trajectory (The DHA-induced stick motion produces a change in trajectory while the IHA-induced stick motion does not).

4. Tuning of the Haptic Feedback Laws and Experiment Organization

In order to compare the three different force conditions DHA, IHA, and NoEF, and to evaluate the effect of actual visual feedback usefulness with respect to the haptic feedback, several experimental runs were performed under three different visibility conditions: (a) Minimum Fog, (b) Medium Fog, (c) Maximum Fog (Fig. 5) and the three different force conditions: DHA, IHA, and NoEF. Note that in Fig. 5, case (c) (Maximum Fog) represents a condition in which the visibility is extremely low and the pilot, de facto, must rely on the haptic cues only. As preliminary assessment of the techniques, in order to test the expected beneficial anticipatory effect of the haptic feedback, and for tuning of the IHA and DHA simulators, a simple experiment with an isolated obstacle was run. The task of the test pilot was to fly straight and avoid an obstacle if found. According to the three visibility conditions described above, the test pilot sees the obstacle from different distances, thus reacts with different delays.

The most evident effect was achieved with the Maximum Fog visibility condition where the pilot was not able to detect the presence of the obstacle early enough to maneuver the UAV without the haptic feedback. As shown in Fig. 6, while in the DHA and the IHA cases no collisions occurred, in the NoEF case a collision occurred confirming the importance to have a haptic feedback in addition to visual feedback to improve the flight safety. The reaction delay difference in the NoEF case, with respect to DHA and IHA, appears clearly from the stick forces plots. Note that a positive F_E force makes the stick move rightwards.

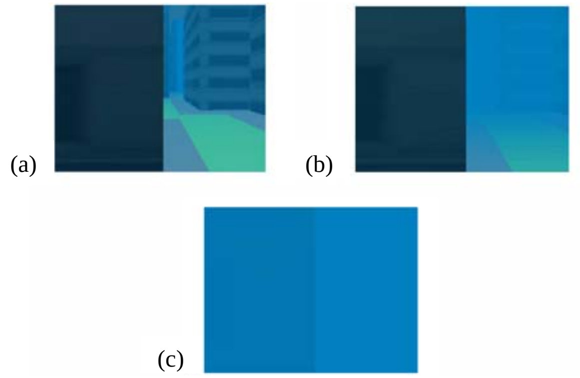

Fig. 5 Out of the window view from the same viewpoint in (a) Minimum Fog; (b) Medium Fog; (c) Maximum Fog visibility conditions.

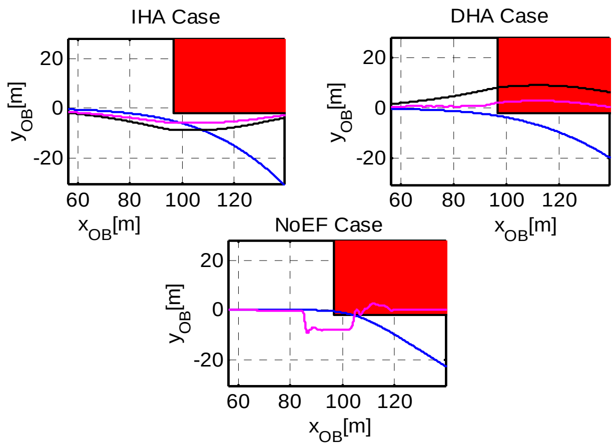

Fig. 6 Isolated obstacle scenario: IHA, DHA and NoEF experiments in the Maximum Fog visibility condition. The obstacle is drawn in red. The lines represent: the aircraft trajectory (blue) starting from the left, the force F_E (black when present) and the total force F (magenta).

5. Experimental Results with the Narrow Street Scenario

After initial tuning of the gain γ with the isolated obstacle scenario, a throughout performance analysis was done using a second scenario. This required the pilot to fly in a narrow street with buildings in both sides; buildings were distributed irregularly so that several turns were needed in order to stay clear and keep "centerline". The task of the experiment was to get to the end of the street without colliding with the buildings. Five different building placements were used to limit the learning effect. Ten naïve pilots participated in the experiment. The trials in the scenarios were mixed and counterbalanced according to the Latin Square Method. The test pilots were informed about the presence of three different force conditions, with no additional specific instructions; the three force conditions were described as: one corresponding to a spring-damper stick with no haptic aid; two other different conditions, named Force-A and Force-B, which try to move the stick that has the same spring-damper characteristics. Pilots were asked to try to recognized and distinguish the three forces, and, after each flight, they were asked to classify them according to what they felt. Regarding visibility, each fog condition was run as a separate block: they had to run 45 trials of about 2 minutes each. The first 15 under the Minimum Fog condition (A), the second 15 under the Medium Fog condition (B), the last 15 under the Maximum Fog condition (C). In total, the experiment lasted about 120 minutes (including instructions and breaks between blocks). Fig. 7 shows three sample simulations with the three force conditions with Maximum Fog; blue line is aircraft path, black line is the haptic aid force, magenta line is the total force. Notice how the haptic force has opposite sign with respect to the trajectory error in DHA and IHA. Notice also the numerous collisions in the NoEF case (aircraft trajectory passing inside the buildings).

In order to numerically assess the performance of the three force conditions, we selected the mean number of collision as performance measure. The mean number of collisions for the three force conditions [NoEF, IHA, DHA] were entered in a one-way repeated measures analysis of variance (ANOVA). Fig. 8 shows the results of the analysis.

A main effect of the force condition was found: [$F(2, 9) = 6.427$, $p < 0.01$]. Post-hoc tests using Bonferroni correction for multiple comparisons, $p < 0.05$ confirmed

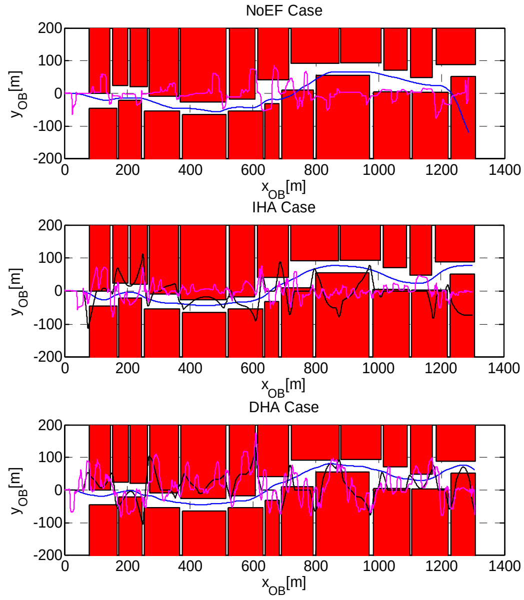

Fig. 7 Three sample simulations performed with the three force conditions and the Maximum Fog visibility condition. The lines represent: the aircraft trajectory (blue) starting from the left, the force F_E (black when present) and the total force F (magenta). The forces depicted are multiplied by 10 N.

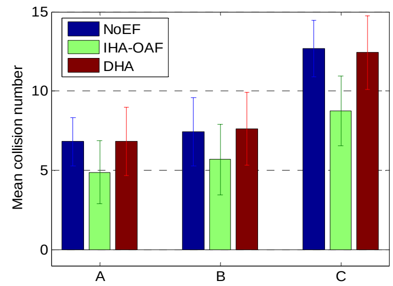

Fig. 8 Performance (mean and standard deviation) for the 3 force conditions (DHA, IHA-OAF, NoEF) and for the 3 visibility conditions (A, B, C).

that the pilots performed significantly better when the IHA-OAF haptic cue was provided in the haptic device. No interaction was found between the force and fog conditions. In other words, the just introduced IHA-Obstacle Avoidance Feel provided the best results in the obstacles avoidance task irrespective of the fog condition. This result was particularly interesting in the case of Minimum Fog condition, for which it was expected that the NoEF case, would produce the best performance with a set of untrained and uninstructed pilots. Unlike what described in Ref. [1], no significant advantage of the

DHA over NoEF was found. We must note, however, that our experiment, and the one described in Ref. [1] have several differences: a different stick stiffness constant; the vehicle dynamics (aircraft vs. helicopter); different force field, and lastly different obstacle scenarios.

After each trial the pilots were asked whether they could recognize the type of forces applied by the haptic system and to classify them. Most of them were capable to distinguish between the spring force condition (namely the NoEF) and the force feedback conditions (both A Force and B Force). It was, in general, more difficult to classify and distinguish the A and the B Forces. Some of them correctly noticed and reported the difference between A and B in terms of cue direction with respect to the obstacles (force pushing away from or towards the obstacles). Others commented on a "perceived" difference in force strength, although this was not true because the magnitude of the force in the two conditions was the same when at the same distance from the obstacles. Some classification was poor (until the end of the 45 trials they still were not able to classify and recognize the force conditions). Three of 10 pilots were not able to recognize more than the 40% of the forces during the 45 trials. Only 6 of 10 pilots were able to recognize more than the 60% of the trial forces. Only 3 of them were able to recognize more than 75%. After the 45 trials, participants were interviewed separately. In order to compare the results, each pilot was asked to fill out a questionnaire with 6 questions in Table 1. Only the pilots who recognized more than 75% of the forces were considered in the analysis (See Fig. 9).

Fig. 10 shows instead the answers of the 6 participants capable of recognizing only the 60% of the trial forces. The haptic cues (both DHA and IHA-OAF) were judged to have strongest forces (Questions A), and the forces which required the most efforts (Questions D) with respect to the NoEF. DHA and IHA-OAF were also considered to provide the best help (Questions B). No definite preference for the evaluation of their own performance in the task was given (Question E), nor the condition which gave them the best control of the UAV (Questions C), or their own preference between the forces (Questions F).

Table 1 The questionnaire to the participants.

ID	Question text
A	Which force condition was stronger?
B	Which of the two conditions do you think was more helpful?
C	Under which condition you think you had the best control on the aircraft?
D	In which condition you think you had to produce the largest effort?
E	In which of the condition you think you had the best performance?
F	Which of the conditions did you prefer?

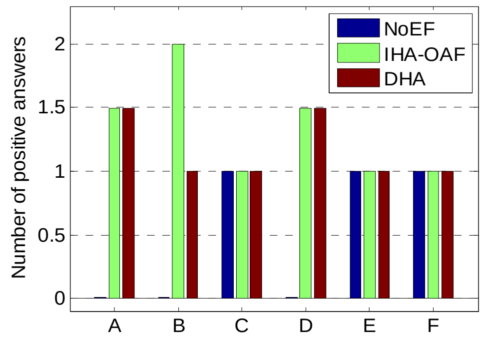

Fig. 9 Participants answers to questionnaire for the 3 participants who recognized 75% of the trial forces.

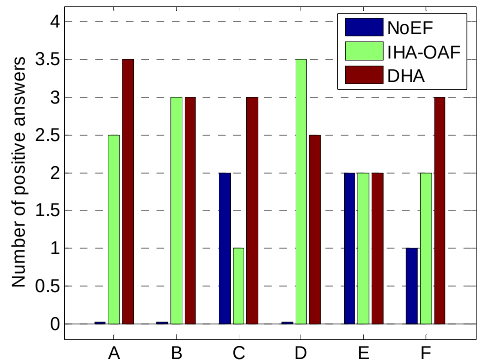

Fig. 10 Participants answers to questionnaire for the 6 participants who recognized 60% of the trial forces.

6. Conclusions

The paper presented experimental results on the effects of two different haptic aid paradigms for obstacle avoidance support, and compared them against the baseline case with no haptic feedback. The aim of the experiment was to test whether the employment of a newly developed IHA-OAF (Obstacle Avoidance Feel) would produce improvement over other approaches currently present in literature. Our tests showed that Indirect Haptic Aid could provide better help for participants than the Direct Haptic Aid and a baseline case (NoEF case) in an obstacle avoidance task with a simulated UAV. This confirms the importance of having a haptic feedback in addition to visual feedback to improve the flight safety in case of (tele-)operated systems even in pretty good visibility conditions.

The results show that the performance when using the IHA-OAF approach are significantly better than with the other two types of force feedback (DHA and NoEF). The results of the participant's questionnaire analysis indicate that most participants felt that the DHA and IHA presented largest forces and required the most efforts but also were the most helpful forces with respect to the baseline NoEF. The degree of helpfulness of the haptic cues (both DHA and IHA-OAF) is paid in terms of additional pilot effort, but this was considered a good compromise between workload and performance.

We can conclude that a haptic cueing system based on the IHA approach is capable of providing enough additional information to the pilot for an obstacle avoidance task. It represents a viable alternative to other approaches known from the literature where a DHA approach is used.

Acknowledgments

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