Evaluation of Direct and Indirect Haptic Aiding in an Obstacle Avoidance Task for Tele-Operated Systems

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Abstract: The sense of telepresence is very important in teleoperation environments in which the operator is physically separated from the vehicle. It appears reasonable, and it has already been shown in the literature, that extending the visual feedback with force feedback is able to complement the visual information (when missing or limited) through the sense of touch and allows the operator to better perceive information from the remote environment and its constraints, hopefully preventing dangerous collisions. This paper focuses on a novel concept of haptic cueing for an airborne obstacle avoidance task; the novel cueing algorithm was designed in order to appear "natural" to the operator, and to improve the human-machine interface without directly acting on the actual aircraft commands. An experimental evaluation of two different Haptic aiding concepts for obstacle avoidance is presented. An existing and widely used approach, belonging to what we called the Direct Haptic Aid (DHA) class, and a novel one based on the Indirect Haptic Aid (IHA) class. The two haptic aids were compared with a baseline condition in which no haptic force was associated to the obstacles. Test results show that a net improvement in terms of performance (i.e. the number of collisions) is provided by employing the IHA haptic cue instead of both the DHA haptic cue and the visual cue only. Most participants of the experiment reported the strongest force feeling, the most necessary effort and also the most helpful sensation with DHA and IHA conditions with respect to the baseline condition. This paper shows that the IHA philosophy is a valid alternative to the other commonly used, and published in the scientific literature, approaches which fall in the DHA category.

Keywords: Haptics, Teleoperation, Remote control (Remotely Piloted Vehicles), Human-machine interface, Telepresence, Obstacle avoidance, Multi-sensory interface.

1. INTRODUCTION

The aim of this work is the investigation of a novel haptic aid for teleoperated systems. In the context of teleoperated systems, where visual cues only have usually been used, the adoption of an artificial feel system for the stick appears to increase the 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). Tactile cues have shown to complement the limited visual information (given by the visual displays of a remote Control Ground Station, CGS) and improve the efficiency of the teleoperation as Lam et al. (2009a, b) stated. This paper focuses on the investigation of a haptic aid system, for an airborne obstacle avoidance task, that is alternative to what is already present in the literature and exploits the concept of Indirect Haptic Aid (Alaimo et al., 2010a, b). Haptic cues in supporting collision avoidance have always been represented by repulsive forces created by objects in the environment in order to help the operator to avoid them. Research on autonomous ground mobile robots usually involves virtual repulsive forces to avoid collisions with obstacles (Lam et al., 2009a, b; Diolaiti et al., 2002; Barnes et al., 1999; Farkhatdinov et al., 2010; Horan et al., 2007; Mitsou et al., 2006; Rösch et al., 2002; Sangyoon et al., 2002). 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 was named Direct Haptic Aiding (DHA) (Alaimo et al., 2010b). In general in this case the operator has to 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, by letting him/her know what is happening in the remote environment and leaving him/her the full authority to take control decisions. The haptic feedback law must be designed to infer a perception to the operator regardless of the fact that the resulting haptic force, if considered alone without human contribution, might even affect "negatively" the command given to the system. As far as we have experienced, in a IHA system if often happens that the operator, while performing his task, has to oppose to the force felt on the haptic device. The just described class of Haptic aids was named Indirect Haptic Aiding (IHA) (Alaimo et al., 2010a, b) since it is clear from the above definitions, that these two classes of haptic aids are complementary. Furthermore, when a haptic input requires a reaction in opposition to a stimuli rather than compliance, it might appear more 'natural' to the human being because it exploits the highly automatic and fast stretch response (Kveraga et al., 2002 and Smidth & Lee, 2005) and the authors believe that the stretch response is involved in this case. To the authors' knowledge, another work only, not dealing with teleoperation issues, nor with obstacle avoidance, but regarding path following for a manned aircraft exists that, could be classified as belonging to the IHA class (De Stigter et al., 2007); within this work the authors suggest to use 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.

2. THE SIMULATION ENVIRONMENT

A simulated flight experiment was set-up by using a linear aircraft simulator implemented by using a Matlab/Simulink simulation. The selected aircraft model was a linearized version of the De Havilland

Canada DHC-2 Beaver implemented using the Simulink Flight Dynamics and Control Toolbox (Rauw, 1997). The control stick was simulated by using a high precision force feedback device (omega.3, Force Dimension, Switzerland) which provided control stick simulated force up to *12 N*. A virtual environment (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 software package (Pollini et al. 2000). The environment was constituted by a ground plane, the sky and buildings with regularly spaced windows to reproduce an appropriate perception of depth. We prepared a simple control task: the aircraft had to be flown in an urban canyon with buildings placed irregularly (non Manhattan-like) along the desired path; thus, the buildings constituted a narrow street with buildings in both sides. The task of the experiment was to get the end of the street by avoiding the collisions with them.

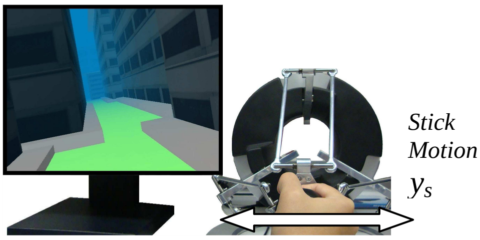

Fig. 1. The experimental setup. Upper left section shows a sample out of the window view of the scenario; lower right shows the Omega Device and the Y axis degree of freedom.

In order to limit pilot workload and possible errors, the aircraft lateral dynamics only (i.e. roll and heading angles and lateral position) had to be controlled by the pilot. The aircraft velocity was constant (about *50 m/s*).

2.1 The Haptic Force Felt on the Stick

Since only the lateral aircraft dynamics, which is usually controlled using lateral stick motion (the roll channel), was simulated, then only lateral (along the Omega Device Y axis) motions were allowed on the the stick. The haptic force was selected, as common practice, to be a combination of two constant stiffness and damping terms and an external force to be defined by the haptic aid algorithm. Given the lateral stick displacement y_S, and lateral stick displacement velocity $\dot{y}_S$, the force $F_{S,yOD}$ felt by the operator during the obstacle avoidance task along the Omega Device *y* axes is:

$$F_{S,yOD} = K_{el} \cdot y_S + K_d \cdot \dot{y}_S + F_E = F_{el} + F_d + F_E \qquad (1)$$

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, the elastic and the damping one, will be present in all of the three conditions of the experiments. The third one is indicative of the condition of the external force. In this experiment three types of external force F_E were compared: DHA, IHA and a baseline force condition (No External Force, NoEF) in which $F_E = 0$ in order to verify that 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).

2.2 The Obstacle-generated Force Field

In order to produce the haptic feedback on the stick with the goal of helping to avoid collisions with obstacles, we defined a force field around the obstacles. Force vectors start in the center of each single obstacle and point away radially from the obstacle. The intensity of the force field decreases with distance from the obstacle border and becomes zero beyond a certain threshold distance. The force field produced by the total number of obstacles is given by vector sum of the force field generated by each single obstacle. This force should not be confused with the actual force on the stick; this force field will be used as a "distance sensor" to produce the two different haptic sensations. The total force $\mathbf{F}_{\mathbf{E,OBS}}$ exerted by the environment at the position of the aircraft centre of gravity (in both force types, DHA and IHA), in the obstacle reference frame (the fixed Earth Reference Frame: x_{OB} axes points North, y_{OB} axes point East) is the superposition of the repulsive force produced by each obstacle:

$$\mathbf{F}_{\mathbf{E,OBS}} = \begin{bmatrix} F_{E,xOBS} \\ F_{E,yOBS} \end{bmatrix} = \sum_{i=1}^{N} \mathbf{F}_{\mathbf{E.OB}} \qquad i = 1, \dots, N \qquad (2)$$

where N is the total number of obstacles. For 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. By following this principle, a repulsive force field, in Equation (3), (similar to the one used by Diolaiti at al., 2002) was associated to a collection of rectangular obstacles. Let $\mathbf{p}_{\mathbf{CG}}$, $\mathbf{p}_{\mathbf{OB,C}}$ and $\mathbf{p}_{\mathbf{OB}}$ to be respectively the position of the aircraft centre of gravity, the position of the center of a single obstacle and the sides of the obstacle closer to the aircraft; the line of the force field at position $\mathbf{p}_{\mathbf{CG}}$ was selected to be aligned with the unity vector $(\mathbf{p}_{\mathbf{OB,C}} - \mathbf{p}_{\mathbf{CG}}) / \|\mathbf{p}_{\mathbf{OB,C}} - \mathbf{p}_{\mathbf{CG}}\|$, the conjunction between the aircraft center of gravity and the center of the obstacle, and the field intensity is linearly decreasing with the distance $d(\mathbf{p}_{\mathbf{OB}},\mathbf{p}_{\mathbf{CG}})$ of the point $\mathbf{p}_{\mathbf{CG}}$ from the nearest point of the obstacle boundary. Thus, the vector $\mathbf{F}_{\mathbf{E,OB}}$ of the force field is:

$$\mathbf{F}_{\mathbf{E,OB}} = \begin{cases} -k_e \cdot \left(d(\mathbf{p}_{\mathbf{OB}}, \mathbf{p}_{\mathbf{CG}}) - r_e\right) \cdot \dfrac{\mathbf{p}_{\mathbf{OB,C}} - \mathbf{p}_{\mathbf{CG}}}{\|\mathbf{p}_{\mathbf{OB,C}} - \mathbf{p}_{\mathbf{CG}}\|}, & d(\mathbf{p}_{\mathbf{OB}}, \mathbf{p}_{\mathbf{CG}}) < r_e \\ 0, & \text{otherwise} \end{cases} \qquad (3)$$

where k_e is an appropriately selected constant. Only when the distance $d(\mathbf{p}_{\mathbf{OB}},\mathbf{p}_{\mathbf{CG}})$ is less than the maximum distance of influence r_e (which was set to *50 m* in our experiment), a haptic force is generated at the Haptic Device; otherwise the pilot feels only the constant stiffness and damping of the stick.

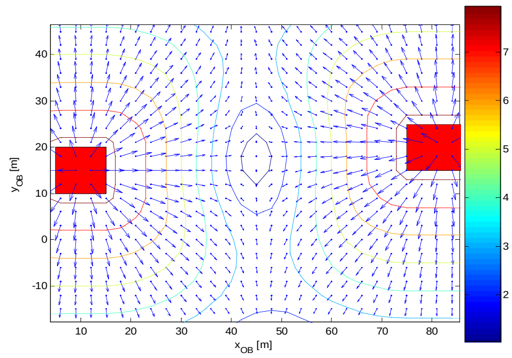

Fig. 2. Sample obstacles-generated force field.

Figure 2 shows an example of the force field with force vectors and iso-intensity contour lines that is produced by the obstacles. Value and direction of the force field at the current position of the aircraft are used in the simulator to generate the haptic sensation. As anticipated, the total force exerted by the obstacles (2) is expressed in the fixed Earth Reference Frame. Since aircraft speed is constant and cannot be changed to avoid obstacles, it appears reasonable to use only the projection of the force field on the lateral axis of the aircraft to generate the aid forces. Thus a change in the aircraft Body Reference Frame is necessary to appropriately select the force component that lies on the lateral axis of the current aircraft direction:

$$\begin{bmatrix} F_{E,xB} \\ F_{E,yB} \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} F_{E,xOBS} \\ F_{E,yOBS} \end{bmatrix} \quad (4)$$

where $F_{E,xB}$ and $F_{E,yB}$ are the force components in the aircraft Body Reference Frame (origin in the centre of gravity of the aircraft, $\boldsymbol{x_B}$ is in the vertical plane of symmetry of the aircraft and points the nose of it, $\boldsymbol{y_{OB}}$ axes is in the plane perpendicular to the plane of vertical symmetry and points to the right side) and ψ is the heading angle of the aircraft. For the above considerations, only the $F_{E,yB}$ component will be used to generate the Haptic feedback.

3. DHA SIMULATOR SETUP FOR OBSTACLE AVOIDANCE TASK.

The motivating idea of the DHA force is taken from previous works in which haptic cues supported collision avoidance. Usually, as introduced above, 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. Research on autonomous ground mobile robots usually involves virtual repulsive forces to avoid collisions with obstacles (Lam et al., 2009a, b; Diolaiti et al., 2002; Barnes et al., 1999; Farkhatdinov et al., 2010; Horan et al., 2007; Mitsou et al., 2006; Rösch et al., 2002; Sangyoon et al., 2002). These works could 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 to the obstacles, $F_{E,yB}$, 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 avoiding the obstacle. When the distance $d(\mathbf{p_{OB}},\mathbf{p_{CG}})$ in Equation (3) is less than r_e, a repulsive force is sent to the Haptic Device in order to let the aircraft make a turn in the opposite direction with respect to the obstacle. No influence is exerted by obstacles located at distance greater than r_e and the increase in the repulsive force $\mathbf{F_{E,OB}}$ is a linear function of the distance $d(\mathbf{p_{OB}},\mathbf{p_{CG}})$. Figure 3 shows a simplified block diagram of the DHA simulator, where, $F_E = F_{E,yB}$ of Equation (4), F_h is the force exerted by the human operator who receives both the proprioceptive and visual feedback, and F is the total forces exerted on the control device.

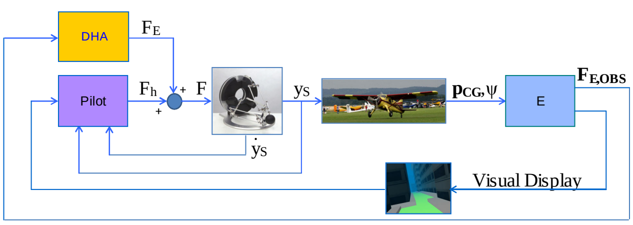

Fig. 3. DHA Simulator Scheme.

4. IHA SIMULATOR SETUP FOR OBSTACLE AVOIDANCE TASK.

The motivating idea of the first IHA force feedback designed by the authors for UAV teleoperation was inspired by the fact that pilots who fly inside mechanically driven aircraft “feel” the external environment (e.g. aerodynamic disturbances, wind gusts, etc) by the effect they have on the control stick (Alaimo et al., 2010a), while a pilot in a remote Ground Control Station does not. Thus, in order to increase the pilot situational awareness, by measuring relevant aircraft dynamic variables like angle of attack and load factor, this feeling was artificially reproduced on the haptic device resulting in a valid aid for wind gust rejection during a altitude hold task. Although the haptic force was not designed in order to help the pilot to reject the wind gust, and, to certain extent, even disturbed him, it successfully increased the pilot situational awareness in terms of external disturbances since mean performance was improved with respect to the case of no haptic aiding. Even a reduction of pilot reaction time to the wind gust was noticed. In the case of the obstacle avoidance task, which is studied in this paper, no “real” stick sensation can be associated with the obstacle proximity, thus an artificial feedback on the stick was created following the IHA philosophy: the artificial force field generated by the obstacles, which is a function of obstacle proximity was used to produce a disturbance-like sensation to which the pilot had to react.

4.1 IHA for obstacle avoidance task concept

The design of a IHA-inspired obstacle avoidance aid appears complex since no force sensation is ”naturally” generated by coming close to an obstacle. But, in order to follow the concept that already was proven to be successful in the gust rejection task, that opposition to haptic stimuli is a ”more natural” pilot reaction with respect to compliance to stick motion, a haptic aid of opposite sign with respect to the DHA one was designed. This type of aid would result in a tendency of the aircraft to fly toward the obstacle instead of flying away from it as in DHA. Thus, in order not to penalize too much the expected IHA system performance, and to make it safe, the indirect force feedback (the same as the direct force feedback in Equations (1)-(4) but opposite in sign) was transformed in a shift of the neutral point of the stick. This means that only the stick, de facto, would move towards the obstacle 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 exact example, the stick motion will induce the aircraft to fly away from the obstacle. What happens if the pilot is touching the stick? In accordance with Schmidt and Lee (2005), when the stick moves 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, 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 on the left that is, in the example, the maneuver to perform to fly away from the obstacle. The vanishing of the haptic cue informs the pilot that the obstacle is far away and not dangerous anymore. In other words, the IHA for obstacle avoidance task follows the general IHA concept described before: it provides to the pilot the information about the presence of the obstacle on a side of the aircraft; this helps him/her indirectly by letting him/her know 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. Figure 5 shows the employed IHA Simulation Scheme. This haptic aid was named *Obstacle Avoidance Feel* (OAF).

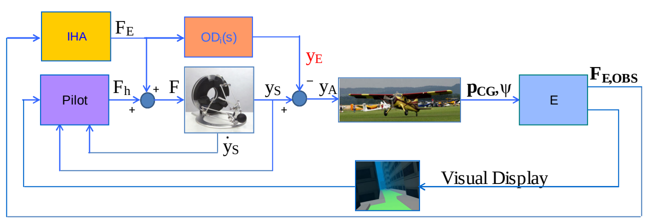

Fig. 5. *IHA Simulator Scheme*

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 external force F_E, is sent to both the real Omega Device and a numerical model of it (the OD_i *block* in Figure 5). 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; thus the actual aircraft input $\delta_A=0$ if $F_h=0$ altought the stick was moved by the effect of F_E . The force F_E has the only effect of changing the neutral position of the stick. A detailed analysis follows. Let $OD(s)$ to be the transfer function of the real Omega Device (by supposing that the real Omega Device has a linear behavior and representing it through a transfer function is possible) and with $OD_i(s)$ the transfer function of the identified model of it. Let the displacement of the real Omega Device end-effector and the displacement of the identified model of it be respectively y_{OD} and $y_{OD,i}$. Let us to suppose that by giving the same input, F_E, to the Omega Device and to its identified model the output, the produced displacement, is the same in both cases: $y_{OD} = y_{OD,i}$ (i.e. the identified model is exact); the net result is that the operator moves the end-effector by δ_A through the application of the force F_h. As a matter of fact, from the Figure 6:

$$\begin{cases} F_h + F_E = F \\ y_S - y_E = \delta_A \end{cases} \quad (5)$$

$$\begin{cases} y_{OD} = OD(s)\cdot F_E = OD_i(s)\cdot F_E = y_{OD,i} = y_E \\ y_S = OD(s)\cdot F = OD(s)(F_h + F_E) = OD(s)\cdot F_h + y_E \end{cases} \quad (6)$$

From the second of Equation (5) and the second of Equation (6):

$$\delta_A = OD(s)\cdot F_h \quad (7)$$

The final result is that the F_E changes just the neutral point of the Omega Device by δ_E and the only input to the aircraft dynamics is δ_A of Equation (7). 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 (Ljung, 1999):

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

4.2 The IHA External Force

Following the IHA concept, for this specific obstacle avoidance scenario, the sensation to be produced on the stick was selected to be of same magnitude but of opposite sign to that provide by the DHA approach. Figure 6 shows a simplified block diagram of the DHA simulator, where F_E=-$F_{E,yB}$ of Equation (4). Nonetheless, it has to be remembered that in the IHA case, as anticipated, the external force is used to move the neutral point of the stick without causing the aircraft to fly towards the obstacles. As said, the goal of this research is to show that the IHA approach, which, roughly speaking, produces haptic sensations of opposite sign than the DHA case, can provide enough richness of information to the pilot without affecting directly aircraft trajectory (the DHA-induced stick motion produces a change in trajectory while the IHA-induced stick motion does not). And maybe, also in terms of performance (e.g. the number of collisions) IHA approach could bring some improvement (see later).

5. TUNING OF THE HAPTIC FEEDBACK LAWS AND EXPERIMENTAL DESIGN

In order to compare the three different force condition: DHA; IHA; and NoEF, and to evaluate the effect of actual visual feedback usefulness with respect to the haptic feedback, several experiments were run under three different visibility conditions: a) Minimum Fog; b) Medium Fog; c) Maximum Fog (Figure 6) and the three different force condition: DHA; IHA, and NoEF. As can be seen in Fig. 6, the Maximum Fog case (c) 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 and for tuning of the IHA and DHA simulators, a simple experiment with an isolated obstacle was run (Section 5.1). Then, a more complex scenario was used: the narrow street scenario described below (Section 5.2).

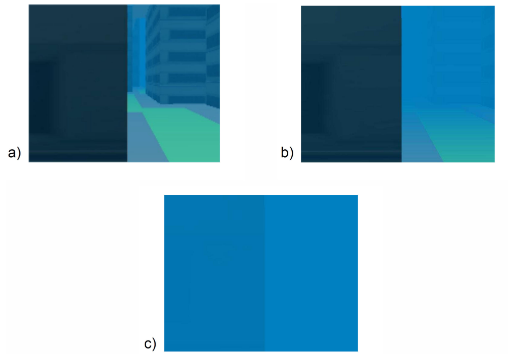

Fig. 6. Out of the window view from the same viewpoint in a) Minimum Fog; b) Medium Fog; c) Maximum Fog visibility conditions.

5.1 Isolated Obstacle Scenario

In order to test the beneficial anticipatory effect of the haptic feedback several experiments were run using a scenario with an isolated obstacle placed along the path of the aircraft; the task of the participant was to fly straight. The participant sees the obstacle from different distances, according to the three visibility conditions described above. The most relevant test performed had the Maximum Fog visibility condition: the participant was not able to detect the presence of the obstacle early enough to maneuver the aircraft without the haptic feedback; as can be noted in Fig. 7, 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 in the NoEF case, with respect to DHA and IHA, appears clearly from the stick forces plots.

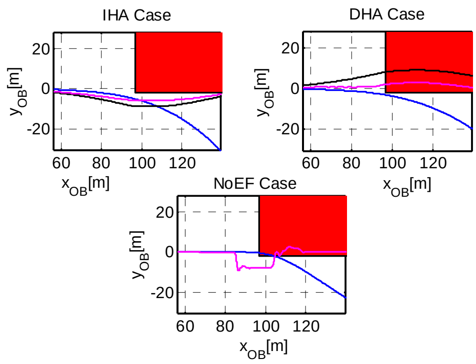

Fig. 7. Isolated obstacle scenario: IHA, DHA and NoEF experiments in the Maximum Fog visibility condition. The obstacle is drawn in red. The lines represent: the aircraft trajectory (blue) starting from the left, the force F_E (magenta when present) and the total force $F_{S,yOD}$ (black).

5.2 Narrow Street Scenario

The second scenario requires the participant to fly in a narrow street with buildings in both sides. The task of the experiment is to get to the end of the street by avoiding the collisions with the buildings.

Five different scenarios (i.e. position of the obstacles) were used to avoid the effect of learning in test participants; Figure 8 shows one of the five scenarios used.

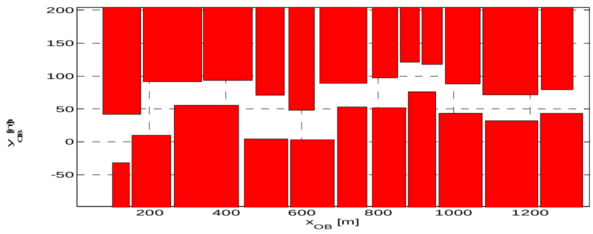

Fig. 8. Sample Narrow Street scenario.

6. EXPERIMENTAL RESULTS

Ten naive participants participated in the experiment. All had normal or corrected-to-normal vision. They were paid, naive as to the purpose of the study, and gave their informed consent. The experiments were approved by the Ethics Committee of the University Clinic of Tübingen, and conformed with the 1964 Declaration of Helsinki. All the trials in all scenarios have been mixed and counterbalanced and no instructions were given about the three different force conditions to test natural reaction of the participants to the three different conditions. Each fog condition was run as a separate block, i.e., the experiment consisted of three successive blocks. 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). As concerning the instructions to the participants: they were informed about the presence of three different force conditions. One in which only the stick was felt as a normal joystick (if they left it, it would come back to the center neutral position) named Spring Force. The other two conditions were said to produce a force which would have tried to move the stick itself named A Force and B Force. They were asked to try to recognize the type of forces trying to classify it according to what they felt. After each trial they were asked what kind of force they felt. The mean number of collision was used 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). Figure 9 shows the results of the analysis.

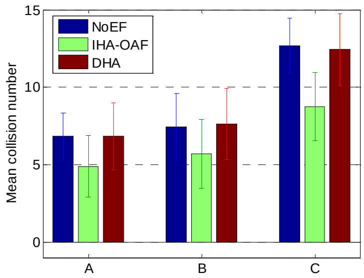

Fig. 9. Performance (mean and standard deviation) for the 3 Force conditions (DHA, IHA-OAF, NoEF) and for the 3 visibility conditions (A, B, C).

A main effect of the fog condition was found: [$F(2,9)=6.427$, $p<0.01$]. Post-hoc tests using Bonferroni correction for multiple comparisons, $p < 0.05$ confirmed that the participants performed significantly better when the IHA-OAF haptic cue was provided in the haptic device than when both DHA and NoEF were provided. No interaction was found between the two variables. In other words, the just introduced IHA-Obstacle Avoidance Feel was proved to provide the best results in the obstacles avoidance task irrespective of the fog condition. Thus, the participants collided less times aided by the IHA-OAF than both the DHA and the NoEF cases. This is a pretty surprising result as it was expected that NoEF case would have produced the best results in presence of Minimum Fog condition. While, according to the present results, the employment of IHA-OAF improves the performance with all the visibility conditions. Furthermore, better performance of the DHA than the NoEF was expected in presence of both Minimum and Maximum Fog conditions. This seems to be against previous results (Lam et al., 2009a). A possible explanation is that under both the DHA and the IHA conditions a haptic help (not given in the NoEF case) was given in finding again the main street once it was lost right after a collision. This is due to the presence of the non null force field inside the obstacle in case of both DHA and IHA. Thus, while in the NoEF case it was not possible to find again the main street once collided, with both DHA and IHA cases it was easier; even if, to be precise, the best help in finding again the main street is given by the DHA which gives the clearest suggestion about where to go to get out from the collided building because being compliant already helps a lot. Another possible explanation is the different type of baseline condition employed: a difference in the stiffness constant chosen (*120 N/m* of the present work against about *200 N/m* of the previous one).

Furthermore, after each trial the participants were asked what kind of force they felt to check if they could recognize the type of forces trying to classify them. Most of them were capable to distinguish between the Spring Force condition (see Section 5.2) 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). Other participants were only able to identify the difference in strength (actually not present because the amplitude of the force in the two force conditions was exactly the same for the same distance between the aircraft and the obstacles). Someone's classification was really poor (till the end of the 45 trials they still were not able to classify and recognize the force conditions). Three of 10 participants were not able to recognize more than the 40% of the forces during the 45 trials. Only 6 of 10 participants over 10 were able to recognize more than the 60% of the trial forces. Only 3 of them were able to recognize more than about 75% of the same. After the 45 trials, participants were interviewed separately. In order to compare the results, each participant was asked to fill in a questionnaire with 6 questions in Table 1:

Table 1. The questionnaire to the participants

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?

The answers to the questionnaire of only the 3 participants who recognized more than about the 75% of the forces step by step during the 45 trials, are for sure more meaningful than the others (see Figure 10). Figure 11 shows instead the answers of the 6 participants able to recognize only the 60% of the trial forces. It seems that the haptic cues in general (both DHA and IHA-OAF) were retained to be the stronger forces (Questions A) and the forces which produced the most efforts (Questions D) with respect to the NoEF. But DHA and IHA-OAF were also considered as the most helpful forces (Questions B). Similarly, the NoEF condition was thought to produce no efforts, weaker forces but without proving a useful haptic cue (i.e. not helping at all). About the evaluation of their own performance in the task (Question E), about the condition which gave them the best control on the aircraft (Questions C) and about their own preference between the forces (Questions F) they were more or less divided.

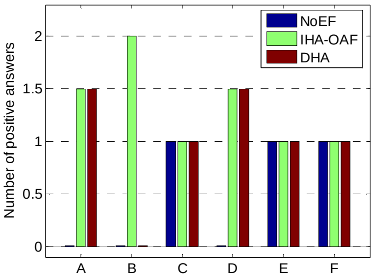

Fig. 10. Participants answers to questionnaire for the 3 participants who recognized 75% of the trial forces.

7. CONCLUSIONS

In summary, the aim of the obstacle avoidance haptic cues evaluation experiment was to test whether the employment of a newly developed IHA-OAF (Obstacle Avoidance Feel) would produce some improvement with respect to other approaches present in literature. It was shown that Indirect Haptic Aid could provide better help for participants than the Direct Haptic Aid and a baseline case (NoEF case, i.e. visual feedback and only the elastic and damping components of the force) in an obstacle avoidance task with a simulated aircraft. This confirms the importance to have 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 is 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 strongest forces and produced the most efforts but also they were the most helpful forces with respect to the baseline NoEF. It seems that the degree of helpfulness of the haptic cues (both DHA and IHA-OAF) has to be paid by feeling the strongest forces and the additional effort, but this seems to be a good compromise for getting the best performance.

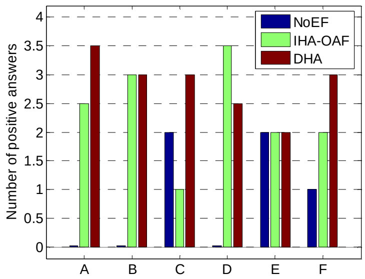

Fig. 11. Participants answers to questionnaire for the 6 participants who recognized 60% of the trial forces.

Thus, we can conclude that a haptic cueing system based on the IHA approach is capable of providing enough richness of information to the participant for an obstacle avoidance task. It configures, at least, as a viable alternative to the other approaches known from the literature where a DHA approach is followed.

8. ACKNOWLEDGEMENTS

The first author, S. M. C. Alaimo, would like to thank Hyoung IL Son for his useful advices about the scenario of the experiment and about the DHA setup. We gratefully acknowledge the support of the WCU (World Class University) program through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology (R31-2008-000-10008-0).

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