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A Comparison of Direct and Indirect Haptic Aiding for Remotely Piloted Vehicles

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Abstract - **The paper presents an experimental evaluation of two different Haptic aiding concepts: Direct and Indirect Haptic Aiding. Two Haptic systems were designed and tested using an experimental setup. The problem of wind gust rejection in Remotely Piloted Vehicles is used as test bench. Test results show the effectiveness of both methods but a better performance of the IHA-based system for pilots without any previous training about the experiment. DHA-based system provided instead better results after some pilot training on the experiment. Pilots reported better sensation of the wind gusts with IHA-based feedback.**

INTRODUCTION

THE aim of this work is the investigation of possible haptic aids for Remotely Piloted Vehicles (RPV).

In the past, the use of artificial feel for manned aircraft equipped with fly-by-wire or servo-assisted flight controls was identified as essential [1]. In the context of RPV, where visual cues only (through the visual display of a remote Control Station) have always been used, the adoption of an artificial feel system for the stick appears to be viable mean to increase the situational awareness, especially in terms of external disturbances and faults which degrade the vehicle maneuvering capability; this is extremely relevant for Unmanned Aerial Vehicles (UAVs). Recent work [2] has shown with a rather complex remote piloting and obstacle avoidance simulations that an appropriate haptic augmentation may provide the pilot a beneficial effect in terms of performance in its task. The main task was to fly from waypoint to waypoint as accurately as possible in an obstacle-laden environment. The authors extensively studied the problem of force feedback (injecting an artificial force on the stick) and stiffness feedback (changing stick stiffness to oppose stick movements). The active deflection of the stick given from the force feedback can be considered an "autonomous collision avoidance" function. In fact, the force feedback can be regarded to yield a "commanded" stick deflection that the operator should follow as much as possible. That is, when yielding to the forces applied on the hand, the operator deflects the stick in a way that satisfies the collision avoidance function. With stiffness feedback instead, the stick becomes stiffer when in the presence of an obstacle, that is, the extra stiffness provides an impedance, resulting in an extra force that depends on the deflection of the stick by the operator. The authors then concluded that a mixed force-stiffness feedback is the best solution. This type of haptic augmentation systems for RPVs was designed in order to help directly the pilot in his/her task by pulling the stick in the correct direction for the achievement of the task, or by changing stick stiffness in order to facilitate or oppose to certain pilot's actions [2], [3]. The class of all Haptic aids, like the one just described, 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) [6].

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, indirectly, by letting him know what's happening in the remote environment and leaving him the full authority to take control decisions. Thus, according to this approach, an Haptic System should aim at increasing the situation awareness, that is at inferring a better knowledge of system status and of its external disturbances. This approach requires that the operator is somehow capable of understanding the meaning of a specific Haptic feedback and of translating it into an information which, in turns, will help him/her to perform the task. This class of Haptic aids, which is clearly complementary to the previously described one, was named Indirect Haptic Aiding (IHA) [6].

In order to compare the two approaches (Direct and Indirect Haptic Aiding), within the specific field of RPVs control, two simulation environments were prepared.

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I. REMOTELY PILOTED VEHICLES SIMULATION ENVIRONMENT

A simulated flight experiment was set-up by using a fully non linear aircraft simulator to provide a realistic aircraft response. An aircraft simulator was implemented using a Matlab/Simulink simulation. The selected aircraft model was

a De Havilland Canada DHC-2 Beaver implemented using the Simulink Flight Dynamics and Control Toolbox [5].
We prepared a simple control task: the aircraft is initially flying levelled in trimmed condition at constant altitude (*300 ft*); three severe vertical wind gusts, which induce the aircraft to initiate a motion according to its Phugoid mode, are simulated by artificially injecting three control disturbances (elevator impulses) of randomized duration (2, 3 or 3.5 seconds), starting time and sign (upward or downward).

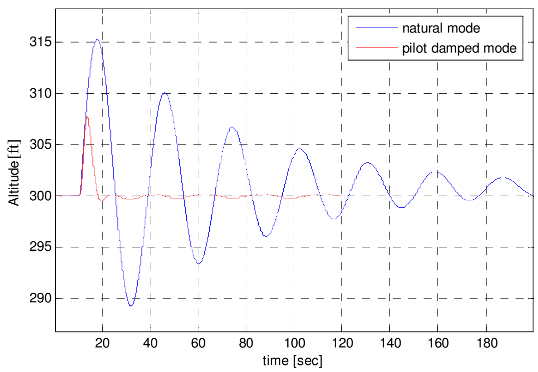

Fig. 1 - Phugoid natural aircraft mode (blue line) versus the typical aircraft response damped by a good pilot (red line).

The Phugoid mode is one of the basic longitudinal flight dynamic modes experienced during the transient phase of an aircraft. It is characterized by complex and conjugate poles that produce a lightly damped oscillation in the aircraft longitudinal variables (velocity, pitch angle, altitude, etc).
During these oscillations, the dynamic pressure, the wing load factor and the aircraft angle of attack change because of the changes in the aerodynamic forces acting on the aircraft.

During this task, the pitch and altitude oscillations of the Phugoid mode have to be damped by the pilot using the stick. Figure 1 shows two sample time histories of aircraft altitude after the injection of the disturbance: one is the uncontrolled aircraft response; the other is the pilot-damped response.

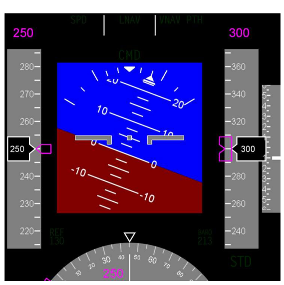

Fig. 2 - Electronic Flight Instrument System (EFIS) display. The airspeed (knots) is displayed on the left, on the right the altitude (feet), and in the center the Artificial Horizon (pitch and roll angle). In our experiment the Artificial Horizon was fixed to zero roll and zero pitch.

A simulated Integrated Flight Display (Figure 2) was used during the experiments to produce the visual cues; this was designed to be as similar as possible to conventional aircraft head-down display. The display shows the relevant variables in the task (pitch, altitude, speed) and the variable to be regulated (altitude) with a magenta reference mark for the set point 300 ft for altitude. In order to focus on the haptic cueing we made the experiment more difficult for the pilots by setting the Artificial Horizon inoperable (zero pitch and roll).

The control stick was simulated using a high precision force feedback device (omega.3, Force Dimension, Switzerland) which provided control stick simulated force up to 12 *N*.

II. IHA SIMULATOR, THE CONVENTIONAL AIRCRAFT ARTIFICIAL FEEL

In order to test the IHA concept, we used a benchmark scenario taken from UAV control. A typical trouble of remote piloting an RPV is the lack of situation awareness because of the physical separation between the pilot (inside the Control Ground Station, CGS) and the airborne RPV. **V**isual feedback only is currently provided by UAVs Ground Control Stations; when an external disturbance or a fault, which on a conventional aircraft would produce a perceptible effect on the stick, affects the RPV, the pilot has to understand this situation by looking at the output of the instruments only. Just as an example for the specific altitude regulation case under consideration in this article. When a vertical wind gust disturbance affects a manned aircraft, the change in angle of attack and wing load are practically instantaneous. This has also an immediate effect on a mechanical-linkage based control stick. The altimeter on the GCS cockpit will though show the resulting change in altitude with a certain delay with respect to the actual disturbance time; as a matter of fact the aircraft dynamics has a low pass behavior and phase lag from angle of attack to altitude (in the simplest linear approximation it behaves as an integrator).

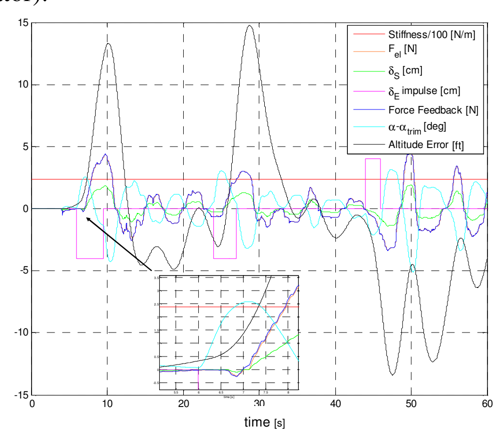

Fig. 3 - Constant stiffness simulation (the operator has a visual feedback and only the elastic component of the force) Altitude response (black line). The green line shows the operator input. The blue line shows the force felt by the operator who is trying to reject the simulated wind gust disturbance (magenta line).

A simulation was run with a constant stiffness stick to simulate a fly-by-wire like situation; the pilot had an Integrated Flight Display as the only instrument showing, aircraft speed, and altitude (Figure 1).

Figure 3 shows the aircraft altitude error (with respect the desired altitude of 300 feet), the pilot command δ_S (i.e. the stick deflection), the disturbance δ_E and the force felt by the pilot trough the stick, which varies linearly with the stick deflection only.

Thus we decided to study if it is possible to improve the performance by improving the pilot situation awareness by adding a Haptic cue, that is a force feedback on the control stick of the CGS, which is, to a certain extent, similar to the actual force he/she would feel on a conventional mechanically driven aircraft.

Taking under consideration the stick force in literature [4], the Conventional Aircraft Artificial Feel (CAAF) Haptic Aiding law was formulated [6] as:

$$F_S = K \cdot \delta_S + K_D \cdot \dot{\delta}_S + F_E = F_{el} + F_d + F_E \qquad (1)$$

Equation (1) shows that the force felt on the stick for the CAAF-IHA is a combination of an external force component F_E, the force of a spring with constant stiffness, F_{el} ($K \cdot \delta_S$), and a damping term, F_d ($K_D \cdot \dot{\delta}_S$), where δ_S and $\dot{\delta}_S$ are stick deflection and velocity of the stick and K is the stiffness The damping term was added in order to avoid oscillations of the Haptic device only, and was tuned heuristically. The constant spring stiffness was selected as:

$$K = K_f \cdot K_q \cdot q_{trim} \qquad (2)$$

where K_q takes into account the effect on the stick of the dynamic pressure $q = 1/2 \cdot \rho \cdot V^2$ (where ρ is the air density and V is aircraft speed) in trim condition (q_{trim}), and K_f is a constant gain which determines the "amount" of force feedback.

As concerning F_E, the stick feel of a conventional aircraft could be reproduced with several levels of successive approximations [1], [4]. In order to keep the force expression simple and its effects easy to analyze, F_E was selected as:

$$F_E = K'_f \cdot K_{\alpha q} \cdot q \cdot (\alpha - \alpha_{trim}) \qquad (3)$$

where K_f' is a constant gain which determines the "amount" of external force, $K_{\alpha q}$ is the weight of the following terms: the dynamic pressure, q, and the difference between current angle of attack α and its trim value α_{trim}. This specific choice is mainly sensible to the change in angle of attack (variations of dynamic pressure, unless very large, have minor effects), amongst all other possible aerodynamic parameters. This choice was motivated by the specific task under consideration: vertical wind gust rejection during an altitude hold; in this particular situation, the angle of attack can be considered the most "informative" type of feedback for the pilot. A different selection could be necessary or provide better results in different situations.

Figure 4 shows the block diagram of the simulation system used to test the IHA concept. The altitude error (between desired altitude H_t and aircraft altitude H) is fed to the pilot P via the visual display; the aircraft speed (V), used to compute dynamic pressure, and the angle of attack are fed to the Haptic device that implements the CAAF-IHA law and feeds-back the force on the stick to produce the stick deflection δ_S (which is used as aircraft elevator control).

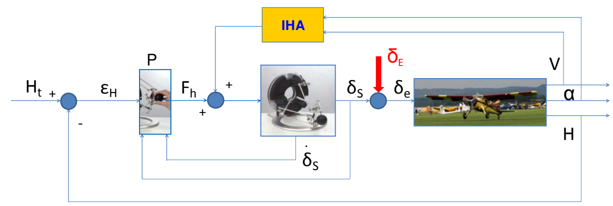

Fig. 4 - IHA Simulator Scheme. The Pilot, P, commands through the end-effector of the Omega Device the simulated aircraft.

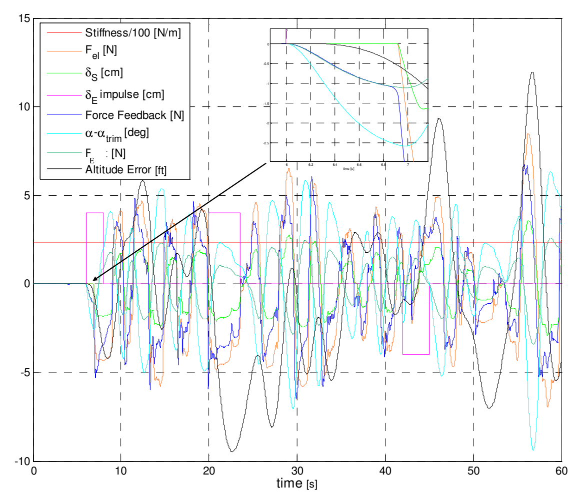

Fig. 5 - IHA + Visual Simulation. Altitude (brown line). The green line shows the operator input. The blue line shows the force felt by the operator who is trying to reject the impulse elevator input (magenta line).

Suppose a downward wind gust affects the aircraft: the angle of attack of the aircraft decreases with respect to the trim condition, the dynamic pressure changes (possibly very lightly depending on the gust speed with respect to the aircraft speed), and the altitude tends to decrease. Within this condition, the CAAF-IHA law produces a negative force F_E; a negative force F_E would produce a positive stick deflection δ_S and thus induces the aircraft to dive even more. The force is immediately felt by the pilot who knows that something has changed. In this specific case the pilot feels a force that pulls the stick away from him, that is to dive, and, he should react immediately, according to his experience, by opposing to the stick motion in order to keep altitude constant. This type of force feedback, roughly speaking with opposite sign with respect to the actual maneuver to be taken, is in complete accordance with the IHA concept.

Figure 5 shows a sample simulation: the force felt on the stick changes as soon as the Haptic device senses a change in angle of attack and triggers the operator response. The lag in the pilot response is noticeable as the stick initially starts deflecting forward before the pilot reacts and oppose to its motion.

III. A Compensator-Based DHA Simulator.

In order to compare the two approaches, a DHA-based simulator setup was designed. According to the DHA concept, a Direct Haptic Aiding system for wind gust rejection should produce a force or a change in stiffness that helps the pilot directly. Thus, a system that produces a force which pulls the stick in the same direction the pilot should do to reject the disturbance, seems appropriate for a DHA control. As a matter of fact, the obstacle avoidance system described in [2], [3] works exactly according to this principle. Stiffness variation, together with force feedback were investigated and found to be able to provide better results than single stiffness or force feedback [3]. Nevertheless, for the purposes of this comparison, we decided to investigate and compare force feedback only.

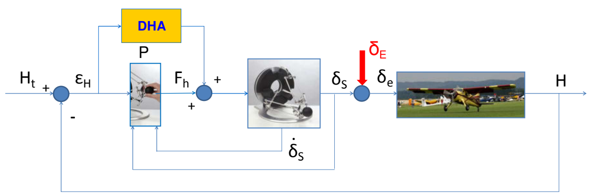

Fig. 6 - DHA Simulator Scheme. The Pilot P and Compensator DHA commands sum at the end-effector of the Omega Device; the compensator output controls the simulated aircraft when the pilot is not in the loop.

The DHA Simulator block diagram is shown in Figure 6. A compensator (DHA block in Figure 6) was added to compute the external force to be felt by the pilot. The Haptic device was controlled as in Eq. 1 to behave as a spring-damper system with an additional force. The additional force F_E was generated by the DHA compensator.

The transfer function of the actual Haptic device (omega.3, Force Dimensions, Switzerland) used in the experiments was identified by using frequency sweeps (from 0.0262 to 10 Hz) and the Empirical Transfer Function Estimate (ETFE) technique [7]. Thus the compensator was designed in order to damp the Phugoid mode and cancel the Omega Device dynamics. The net result is that such compensator can damp effectively the Phugoid mode from altitude measurement only without any pilot: the stick moves and the corresponding stick deflection is sufficient to control the aircraft.

The design of a DHA based augmentation scheme is, in our opinion, very task dependent; the compensator-based design approach described above was viable in our case since the task was specified as holding a reference altitude. This approach could not be used instead when the task cannot be specified as a reference signal to be tracked, or the pilot intention is not known; thus the design of a DHA augmentation scheme could be less straightforward than IHA scheme.

In order to leave the pilot with sufficient control authority, the gain of the compensator was reduced by 60%. Figure 6 shows a simulation using the DHA simulator with the operator out of the loop: the Omega Device end-effector was left free to move, acting, in fact as a very good virtual pilot.

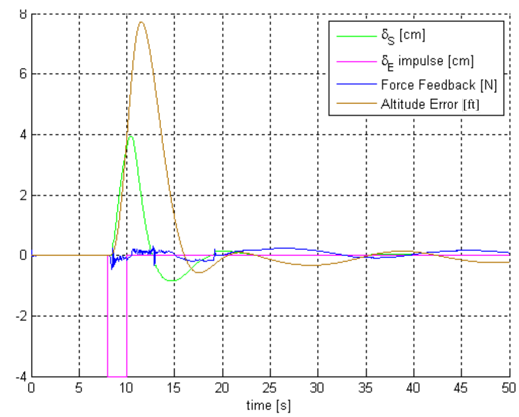

Fig. 7 - DHA without Pilot in the loop Simulation. Altitude response (brown line). The DHA Simulator by itself is piloting the aircraft. The green line shows the operator input. The blue line shows the net sum of haptic aiding and spring force.

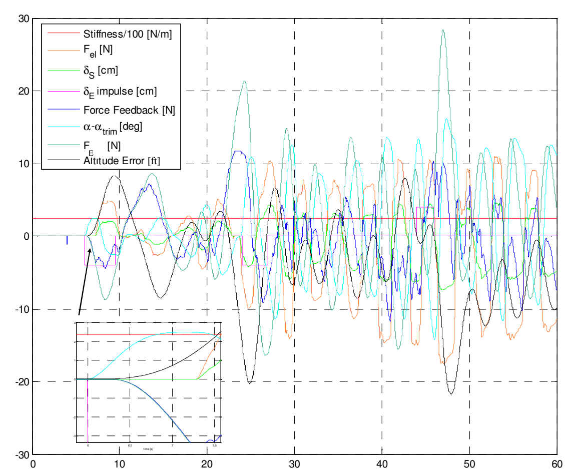

Fig. 8 - DHA with Pilot Simulation. Altitude (black line). The green line shows the operator input. The blue line shows the force felt by the operator who is trying to reject the impulse elevator input who is trying to reject the impulse elevator input (magenta line).

The force feedback plot, in Figure 7, is near the zero line since it results from the net sum of compensator output and the stick spring force: the two forces cancel almost exactly as the virtual pilot behaves as a perfectly compliant pilot to the forces felt on the stick. If the pilot is controlling the aircraft (Figure 8) and the disturbance happens, he perceives immediately that something has happened (the force on the stick changes suddenly as in the IHA case); in this case, according to the DHA concept, the pilot must be compliant to the force and even produces a stronger force in the same direction (since the compensator output was scaled down to 40% of the nominal control effort needed to achieve the control system design specifications).

IV. Tuning of the Haptic Feedback Laws and Preliminary Results

In order to tune the two control laws in terms of gains, damping and stiffness coefficients of the stick and to perform a preliminary assessment, a set of tests were performed with various subjects.

Most of the test subjects stated that they were confused by the motion of the stick with the DHA case since they were disturbed by the fact that he had to start performing a certain manoeuvre without reading any sensible change of altitude. Furthermore the actual pilot commands contain large oscillations in the first trials which may be justified by the confusion the subject reported on what was happening to the system.

A rather different feeling was instead provided by the CAAF-IHA: even though the stick force was felt much in advance of altitude change readings, the action to be taken (opposition to stick motion) was far more intuitive and natural.

Human responses to external stimuli are highly conditioned by the required processing operations. In line with this, some motor responses are more 'automatic' (less affected by cognitive factors) and occur with shorter latency. For instance, saccades are more 'natural' than antisaccades [8]. The stretch reflex, which is a reflex contraction of a muscle in response to passive longitudinal stretching, is an highly automatic motor response that is believed to be the spinal reflex with the shortest latency. Application of the IHA concept to the disturbance rejection problem, which is subject of this article, produced a force stimulus to which the operator must oppose. Several other examples could be built following the IHA concept and would lead to similar results: a stimulus to be counterbalanced and overtaken. Thus, the IHA concept, which requires a reaction in opposition to stimuli rather than compliance, might therefore be more 'natural' for the system because it exploits the highly automatic and fast stretch response.

The type of motion task required by the IHA concept could be thought like being composed by a stretch reflex in response to initial force peak (caused by the gust), together with a higher-level response caused by the experience in rejecting wind gust disturbances and by the visual cues.

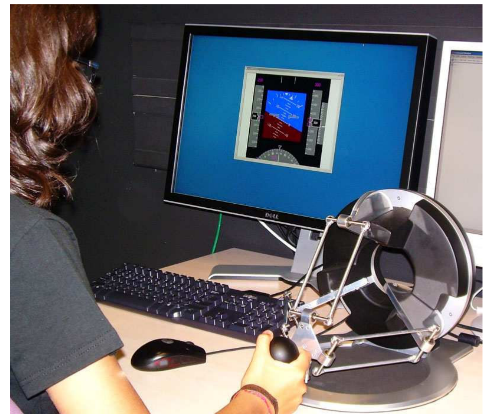

Fig. 9 - Picture of the test setup, showing the display and the haptic device.

V. Test Campaign

In order to validate the preliminary results from our experiments with naïve (non-pilots) subjects we performed a test campaign with a real pilots for the altitude regulation task. The goal of these tests is to compare the effectiveness of the IHA and the DHA concepts for gust rejection during an altitude hold task. In particular we wanted to assess in an analytical way the differences in pilot performance in the two cases. In a recent work [6], the authors used the IAE (Integral Absolute Error) index which proved to be able to measure the performance of the subjects (dependent variable). A smaller IAE of altitude error would indicate a better pilot performance in damping the Phugoid mode. Seven pilots participated in the experiment. The experiment consisted of three different cases: NoFE ($F_E = 0$ in (1)), IHA and DHA. All the trials (36 of 60 seconds each, 12 trials per condition) have been counter-balanced to test natural reaction of the pilots to the three different conditions. Before starting the experiment, every pilot was asked to run a 5 minutes trial where he/she had to perform a slightly different altitude regulation task; the goal of this initial trial, was to let the pilot acquire enough knowledge of aircraft dynamics to be able to pilot it confidently. During this trial a simple spring-damper (the K and K_D constant were chosen as 1/6 of the NoFE case) behaviour of the stick was employed. In total the experiment lasted 90 minutes.

All pilots had normal or corrected-to-normal vision; they were paid 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.

A picture of the test setup showing the haptic device, the actual display and one of the pilots is shown in Figure 9.

VI. Results

Mean IAE values for the three force conditions [NoFE, IHA, DHA] were entered in a one-way repeated measures analysis of variance (ANOVA). When all trials (12 trial for each condition) were considered, no main effect of the type of force was observed, i.e., the three types of force did not differ from one another. We then assessed whether all three types of force feedback were equally 'natural' for the subjects, i.e., whether the first exposure to the different types of feedback gave rise to comparable performance. Here, only the first two trials of each subject for each condition were considered, and the data were entered in the same one-way ANOVA (described above). This analysis revealed a main effect of the type of force feedback [F(2, 12) = 12.943, p<0.01]. As shown in Figure 10, the participants were the least variable in the NoFE and IHA conditions, and the most variable when the DHA force was applied, the variability being significantly worse in this last condition (post-hoc tests using Bonferroni correction for multiple comparisons, p<0.05). In other words, when completely naïve about the aiding schemes (in the first two trials), participants performed significantly better when either no force or the IHA aiding scheme was used than with the DHA aiding scheme.

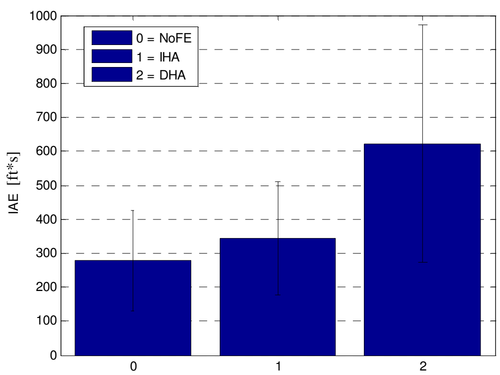

Fig. 10 – *Performance (mean and standard deviation) for the 3 Force conditions.*

Assuming that a certain degree of adaptation and learning of the pilots could have happened during the 12 trials, we also evaluated separately the last five trials of each condition. To test whether this was the case, the mean values of the last five trials were entered in the same one-way ANOVA. The analysis revealed a main effect of the type of force feedback [F(2,12)=13.007, p<0.001]. As shown in Figure 11, the participants were the least variable when the DHA force was applied, and the most variable when both NoFE and IHA forces were applied. Post-hoc comparisons using Bonferroni correction (p<0.05) showed that this difference was significant. In other words, after some training, the DHA approach allowed the best results.

It is worth noticing that, the pilot were not trained explicitly on the three force conditions, and that the trials consisted of a sequence of mixed conditions and not of a uniform batch of the same force condition; thus no explicit training was provided to the pilots on any of the three conditions, but the pilot were quickly capable to understand the DHA functionality and exploit it for improving their performance.

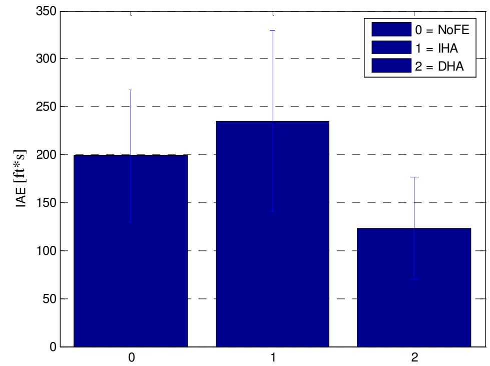

Fig. 11 – *Performance (mean and standard deviation) for the 3 Force conditions.*

After each experiment, pilots were interviewed separately; first of all the pilots were asked to describe their experience and identify the number of different types of sensations they felt during the experiment. All of them identified mainly two classes of force feedback: one which they called "natural", another which they called "autopilot" as they realized, after few tests (from 2 to 4), that in certain experiments the system was providing forces that where oriented in the direction of helping to perform the maneuver (autopilot case) and in other cases the forces where easier to associate with what they were expecting as the aircraft behavior (natural case). Only one pilot realized that some trials were run with the no force case in which the external disturbances give no sensation trough the stick.

Thus, in order to compare the results, each pilot was asked to fill in a questionnaire with 6 questions (Table 1). In each question he/she had to choose, accordingly to the classification of sensations described above, between two different force feedback cases: "Natural" and "Autopilot". According to the discussions with the pilots, we are confident that the Natural case can be mapped to the union of the NoFE and IHA cases, while the Autopilot case maps to the DHA condition.

The 6 questions in the questionnaire are shown in the Table 1:

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?*

Table 1 – *The questionnaire.*

Figure 12 shows the corresponding pilot answers. Most pilots agree that the Autopilot case presented stronger forces and was more helpful (Questions A and B) with respect to the Natural case. Answers to question B and C show a controversial situation: although most pilots voted for the Autopilot as the most helpful, most pilots felt more like being actually piloting the aircraft (Question C) with the Natural case. Pilots' opinions about the workload (Question D) and about the evaluation of their own performance in the task (Question E) were divided. Finally, although it could appear that pilots were going to prefer the Autopilot case, most of them voted for the Natural case. With respect to the latter question, the pilot who voted "not sure" said that he would have voted for the Autopilot case but after a longer training.

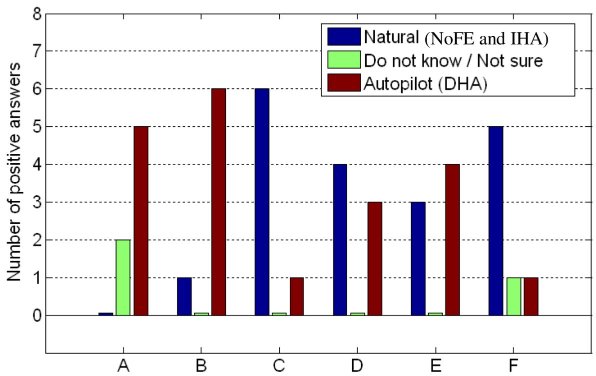

Fig. 12 – *Pilot answers to questionnaire.*

VII. Conclusions

The aim of this experiment was to test whether giving Indirect Haptic Aiding (IHA) could provide better help for pilots than the Direct Haptic Aiding. Participants were provided with haptic cues via a newly developed IHA-CAAF (Conventional Aircraft Artificial Feel). We measured how this type of cueing and the baseline case (NoFE case, i.e. visual feedback and only the elastic component of the force) affected the piloting performance in a gust rejection task with a simulated aircraft.

The results show that when considering all the trials (12 trials for each condition) no significant difference amongst the three types of aiding can be found. When analyzing only the first two trials for each condition, one can observe that the performance when using the DHA approach is significantly worse than with the other two types of force feedback. On the other hand, after some training, this tendency is reversed, the performances observed with the DHA aiding scheme being significantly better than in the other two conditions. Taken together, these results suggest that the DHA is less natural than the IHA (even impairing the performance when compared to a condition in which no force aiding is provided), but that only very few trials are necessary to 'master' it so that it allows significantly better performances than both the IHA and a system without force feedback.

In order to have an idea of what pilots experienced, each pilot was asked to fill out a questionnaire. The results indicate that most pilots felt that the DHA presented stronger forces and was more helpful with respect to both NoFE and IHA. However, most pilots felt more like being actually piloting the aircraft with both NoFE and IHA cases. Pilots' opinions about the workload and about the evaluation of their own performance in the task were divided. Finally, most preferred both the NoFE and IHA feedback conditions to the DHA condition.

We can conclude that the NoFE and IHA case are the most natural forces to the pilots while after some training they can adapt to the DHA force feedback producing the best results even if the workload in this case results to be greater than in the previous cases.

VIII. Acknowledgments

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