Preliminary Evaluation of a Haptic Aiding Concept for Remotely Piloted Vehicles

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Abstract. This paper shows a preliminary experimental evaluation of a novel haptic aiding for Remotely Piloted Vehicles. The aerodynamically-inspired haptic feedback law was named Conventional Aircraft Artificial Feel, and was implemented as a variable stiffness spring. The experimental set-up comprises a fully nonlinear mathematical model of the aircraft, a visual display and a haptic device (a 3 DoF Omega Device). The tests, performed using a set of 18 naïve subjects, show the validity of the proposed approach.

Keywords: Remotely piloted vehicles, experimental evaluation, artificial feel.

1 Introduction

The aim of this research is the investigation of possible haptic aidings for Remotely Piloted Vehicles (RPV). Nonetheless similar techniques could be employed in similar fields like Fly-By-Wire (FBW) piloted commercial aircrafts or helicopters.

The FBW system employed both in large airliners and in military jet aircraft, dispenses all the complexity of the mechanical circuit of the mechanical flight control system and replaces it with an electrical circuit. The FBW makes use of an electronic passive sidestick, in place of the conventional control stick which was connected to the actual aerodynamic surfaces via mechanical linkages. The sidestick is in general implemented as a spring system with constant stiffness that makes the force felt by the pilot stronger as the displacement of the stick increases independently from the particular aerodynamic situation (velocity, load factor). Sometimes the sidestick may provide an artificial vibration of the stick (*stick shaker*) and some acoustical/visual

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warning that makes the pilot to know that the limits of the flight envelope are going to be reached [1].

Completely artificial feel had become essential with fully powered controls [2]. There was considerable speculation about what elements of natural feel should be emulated, coupled with the natural desire to minimise the cost and complexity of the feel devices. The possibilities included control force variation with dynamic pressure (Q feel), speed (V feel) or control deflection only (spring feel), also potentially augmented by devices such as bobweights and downsprings which were already familiar on conventional aircraft. Manual controls also fulfill the role of a tactile display. The human hand can interpret loading forces appearing on the handgrip in terms of demands imposed on the system and its expectable response, enabling the pilot to develop a beneficial phase lead [3].

Artificial feel had become fundamental in addition to the visual cueing in the context of Remotely Piloted Vehicles. Recent work [4] has shown using a rather complex remote piloting and helicopter obstacle avoidance simulation that an appropriate haptic augmentation may provide the pilot a beneficial effect in terms of performance in its task (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 which pulls the stick to fly away from the obstacle) and stiffness feedback (changing stick stiffness to oppose less or more strongly to motion when approaching an obstacle) and 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 [4], [5]. We may group the class of all Haptic Aidings, 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 under the name Direct Haptic Aiding (DHA).

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 this research aims at designing novel haptic augmentation schemes which increase the situation awareness, that is to infer 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 to translate it into a cue which, in turns, will help him/her to perform the task. We may call this class of Haptic Aidings, which is clearly complementary to the previously described one, as Indirect Haptic Aiding (IHA).

An Indirect Haptic Aiding scheme implies that the haptic feedback must trigger the pilot prior knowledge of the force response/dynamics of the vehicle he/she is piloting; as a consequence, the impact of pilot training with a specific force feedback must be accurately understood.

An example of a haptic aiding scheme that follows the IHA concept is shown in the next section.

2 The Conventional Aircraft Artificial Feel

In order to test the IHA concept, we decided to create a benchmark taken form the aerospace field. 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. Currently the remote pilot has got just a visual feedback (visual displays). In case an external disturbance or a fault affects the RPV, that on a conventional aircraft would produce a perceptible effect on the stick, the pilot has to understand this situation by looking at the output of the instruments only. Thus we decided to study if it is possible to improve the pilot situation awareness by adding a haptic cue, which is a force feedback on the control sidestick of the CGS, which is, to a certain extent, similar to the actual force he/she would feel on a conventional mechanically steered aircraft. As a matter of fact, a pilot flying a mechanically steered aircraft feels aerodynamic forces on the stick, which are generated on the actual control surfaces. The simple fact that the pilot feels the load factor (ratio between lift and aircraft weight) helps him to avoid flight conditions which might be dangerous for the aircraft structure. As another simple example, stall may happen during a steep climb maneuver; while approaching the stall condition the stick becomes looser informing the pilot of the risk to lose aircraft control. Furthermore, external disturbances like wind gusts which may be very dangerous if not appropriately and suddenly compensated in a constrained mission environment (e.g., a urban canyon), would produce an immediate effect on the stick.

Useful information like load factor, “distance” from stall and external disturbances cannot be read by the pilot on the GCS cockpit instruments; thus the Conventional Aircraft Artificial Feel (CAAF) haptic aiding scheme was designed in order to provide the pilot with a richer information with respect to the visual display only. The experiments performed try to show and assess analytically that these additional haptic information help the pilot from a performance point of view.

2.1 Forces on the Stick of a Mechanically Driven Aircraft

The force felt by a pilot on the aircraft control column of a mechanical Flight Control System (FCS) during a manoeuvre depends in a very complex manner from all the aerodynamics characteristics of the aircraft, the current state of the aircraft (speed, angle of attack etc.) and of course from stick deflection.

A simplified expression for the force felt by the pilot of a mechanically driven aircraft is [6]:

$$F_S = \eta C_h q S_e c_e G_e = (C_{h0} + C_{h,\alpha}\alpha_h + C_{h,\delta}\delta_e)\cdot qS_e c_e = K_e \cdot \delta_e + F\,. \qquad (1)$$

Where $K_e = C_{h,\delta} S_e c_e q$ and $F = \left(C_{h,0} + C_{h,\alpha}\cdot\alpha_h\right)\cdot S_e c_e q$.

The coefficients in (1) are: C_h is the elevator hinge moment, q is the dynamic pressure of the aircraft, S_e and c_e are the surfaces and the chord of the elevator and G_e is a gearing factor (with units) to convert moments to force and includes the geometry of the control mechanisms, pulleys, push-rods and cables. C_{h0}, $C_{h\alpha}$ and

$C_{h\delta}$ are respectively the elevator hinge moment coefficient at zero lift, the elevator hinge moment coefficient derivative with respect to tail angle of attack changes and with respect to the elevator deflection changes.

This choice is appropriate for studying the longitudinal dynamics of the aircraft (pitch and altitude motion). Thus, we designed an experiment where the pilot has to perform a simple altitude regulation task.

2.2 Implementation on a Haptic Device

In order to keep the force expression simple and easy to implement in a haptic device the force was assumed to be dependent on the two most important variables for defining the flight envelope: dynamic pressure and load factor.

The dynamic pressure is defined as $q = \frac{1}{2}\rho V^2$ where ρ is the air density and V is the airspeed. The load factor $n = \frac{L}{W}$ is defined as the ratio of the lift L to the weight W of the aircraft.

To implement the above-mentioned stimulus on a haptic device, it is necessary to express the total force F_S to be felt by the pilot as a combination of an external force component F_E and a variable stiffness spring with deflection of the stick δ_S and stiffness K.

$$F_S = K \cdot \delta_S + F_E . \tag{2}$$

In order to avoid oscillations of the haptic device a damping term was added:

$$F_S = K \cdot \delta_S + F_E + K_D \cdot \dot{\delta}_S . \tag{3}$$

Where K_D is the damping constant and $\dot{\delta}_S$ is the velocity of the stick. In order to reproduce the force n the stick felt by the pilot during maneuvers on the longitudinal plane the stiffness K was selected as:

$$K = K_f \cdot \left[K_q \cdot q + K_n \cdot (n-1)\right]. \tag{4}$$

Where K_q and K_n are the weights of the dynamic pressure and the differences between the manoeuvre and the one of horizontal flight $(n-1)$ respectively and K_f is a constant gain which determines the “amount” of force feedback.

The gains K_q and K_n was tuned heuristically and the external force was set to zero. Note that the stiffness in (4) contains a dependence on load factor which was not present in (1); the reason for this is to make the pilot aware of the aircraft load factor changes. The final expression of the haptic feedback force becomes then:

$$F_S = K_f \cdot \delta_S \cdot \left[K_q \cdot q + K_n \cdot (n-1)\right] + K_D \cdot \dot{\delta}_S . \tag{5}$$

This expression of the haptic feedback (5) was named Conventional (for mechanically-driven) Aircraft Artificial Feel (CAAF) by its aerodynamically inspired nature. This type of force feedback, in analogy to what found in the artificial feel literature [2], [6] could be addressed as a QN-feel system since the force it generates is proportional to both dynamic pressure (Q) and load factor (N).

3 Methods

In order to test the CAAF (5) concept, a simulated flight experiment was set-up. A fully non linear aircraft simulator was used 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 Flight Dynamics and Control Toolbox [7]. We prepared a simple control task: the aircraft is flying level in trimmed condition and at constant altitude (*300 m* altitude); a disturbance (a -5° elevator impulse lasting 0.5 seconds) is artificially injected at time t=9.5 seconds (the injection time is the same for all the subjects), and the aircraft initiates a motion according to its Phugoid mode. 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 oscillation modes, the dynamic pressure changes because of a change in of the velocity and the load factor changes because of a change in the lift.

The pilot’s task is to keep the aircraft leveled, not oscillating, to restore the initial altitude and to keep it as constant as possible. 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, as an example, the time history of the aircraft altitude in two cases: free aircraft oscillating according to the Phugoid mode and aircraft controlled by the pilot.

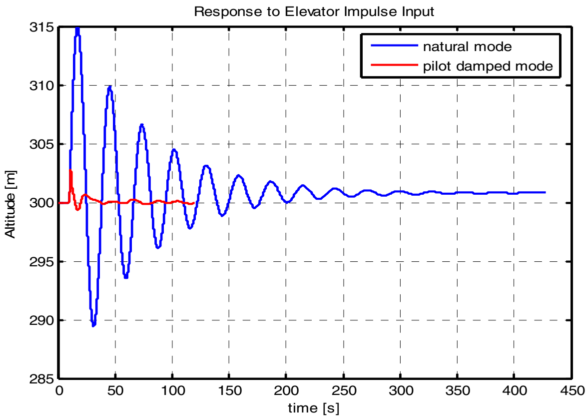

Fig. 1. Aircraft Longitudinal Modes

3.1 The Experimental Test Bed

An experimental test bed was setup in order to test the performance of a set of naïve subjects during the altitude regulation task described above. Figure 2 shows the experimental test bed comprising of a video display and a haptic device.

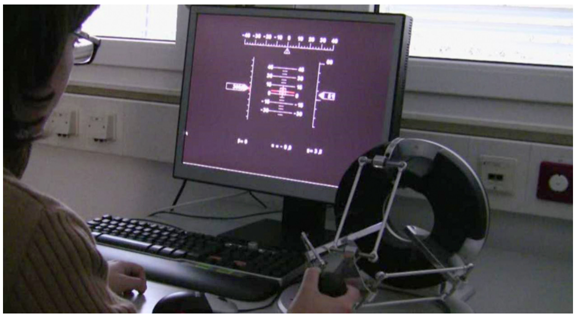

Fig. 2. The experimental test bed

The visual screen displayed during the experiment was a reproduction of a real one; it was designed to be as similar as possible to conventional aircraft head-down display. The display, in white on a black background, shows the relevant variables in the task (pitch, altitude, speed) and the variable to be regulated (altitude) with a red reference mark for the set points: 300 meters for altitude and trim condition (about 5°) for the pitch.

The selected haptic device is the widely used Omega.3 Device; it was used to simulate the control column of a mechanical driven aircraft (Figure 2). The Omega.3 Device with 3DOF was chosen in order to simulate the forward-backward motion of the control bar since only one degree of freedom was needed. The maximum force of 12 *N* which the Omega.3 Device can generate was considered appropriate for the experiment.

3.2 The Experiment

The goal of these tests is to proof whether adding the CAAF kinesthetic (force) cue to the visual cue (a simulated cockpit) improves the control. In particular we wanted to assess in an analytical way the differences in pilot performance in the two cases: with and without CAAF; thus the performance of the subjects (dependent variable) was measured through the IAE (Integral Absolute Error) between the current and desired altitude; a smaller IAE would indicate a better pilot performance in damping the Phugoid mode.

18 subjects (aged 23 to 43, mean 30.7) participated to 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.

The experiment consisted of thee different force conditions: No Force on the end-effector (0) (gravity compensation and K=0, F_E=0), Simple Force (1) and Double Force (2) (twice as much force as in the Simple Force condition achieved by doubling the K_f gain). Each condition was run as a separate block, i.e., the experiment consisted of three successive blocks. The order of presentation of the blocks was counterbalanced.

In total, the experiment lasted from 60 to 90 minutes (including instructions and breaks between blocks). Figure 3 shows sample altitude trajectories taken from one of the experiments; the Simple Force case shows clearly a better performance.

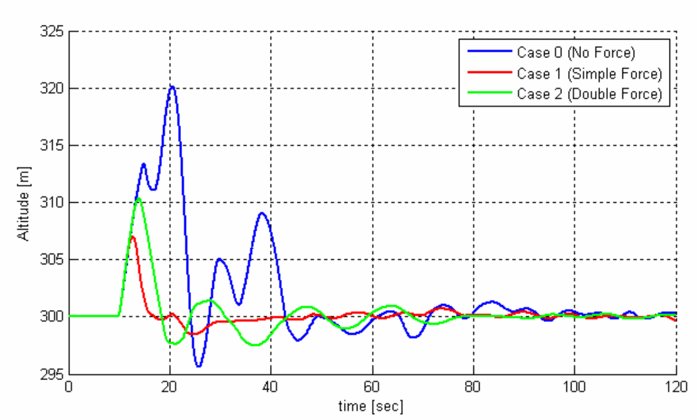

Fig. 3. Comparison of altitude trajectories

4 Results

Mean IAE values were entered in a one-way repeated measures analysis of variance (ANOVA) [No force, Simple force, Double force], which revealed a significant effect of the force factor [F(2, 34) = 7.932, p<0.01]. Figure 4 shows that the participants were the least variable (performed best) when a simple force was applied, the most variable (performed worst) when no force was applied, whereas providing a double force gave rise to 'intermediate' results.

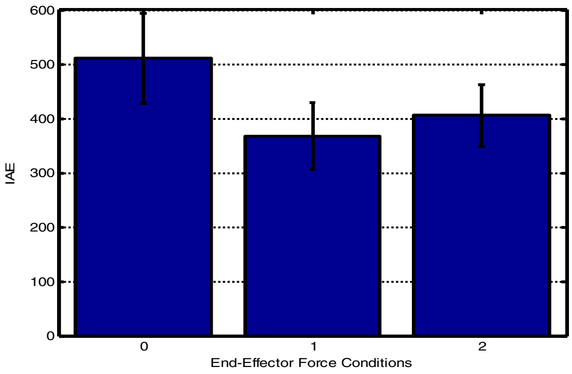

Fig. 4. Performance (mean and standard deviation) for the 3 Force conditions (0: No Force, 1: Simple Force, 2: Double Force)

Post-hoc tests using Bonferroni correction for multiple comparisons ($p<0.05$) indicated that the performance with force (both simple and double) was significantly less variable than without force. In other words, providing CAAF force significantly improved piloting performance as it reduced the variability of the control.

We also assessed the effect of the order of presentation of the blocks with a one-way repeated measures ANOVA [First Block, Second Block, Third Block], which revealed no significant main effect of the order of presentation. In other words, the variability of the performance was comparable irrespective of the order of presentation.

5 Conclusion

The aim of this experiment was to test whether providing Indirect Haptic Aiding could constitute a valuable help for pilots. Participants were provided with haptic cues via a newly developed Conventional Aircraft Artificial Feel. We measured how this type of cueing affected the piloting performance in the Phugoid mode damping task with a simulated aircraft. Our results clearly show that the CAAF facilitates control in this task. Indeed, participants' performance significantly improved when haptic cueing was available. As none of the participants had any experience with piloting, our results suggest that this type of aiding is rather 'natural', as beneficial effects can be observed without any previous learning. In line with these convincing initial results, we are currently investigating the amount of additional information transferred to the operator via the CAAF variable stiffness haptic feedback as compared with other types of haptic aidings (e.g., constant stiffness).

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