Objective evaluation of hand-flying skills and styles in the final approach

Jorg O. Entzinger, Shumpei Kamo, Tsuneharu Uemura, and Shinji Suzuki
The University of Tokyo, School of Engineering, Department of Aeronautics & Astronautics
Bunkyo-ku, Hongo 7-3-1, 113-6568 Tokyo, Japan

Abstract

The dynamics of human pilot control have been studied extensively from a control engineering point of view, but surprisingly little from a human pilot training and evaluation perspective. In this paper we introduce a number of interesting findings relating to the hand-flying skills of student trainees and professional pilots. For this study we focus on landing approaches in a fixed base Boeing 747 simulator. The slow response of this large aircraft requires specific manual control skills, which may remain unnoticed in subjective and flight-path based evaluations. Spectrograms of the elevator control inputs made by the (trainee) pilot show to be a powerful way to visualise general skill differences. We also identified and analysed interesting time-domain characteristics, such as pulsive control styles including half-stepped and reverse (doublet) control, where a sharp, large control input is immediately followed by a smaller or reversed input.

Keywords: *manual flying skill, control style, human pilot, human-machine interaction, training*.

Introduction

Aircraft control, and landing control in particular, requires precise control inputs. Learning the appropriate control inputs for any situation takes considerable time and effort, whether it is for an airline pilot to become captain, for a hobbyist to safely operate a drone, or for an engineer to develop a robust autopilot. Even after more than hundred years of controlled flight, pilot trainees still have to learn the most elementary control skills needed for stabilized flight or attitude changes through extensive practice. Instruction focuses on visual cue use, and feedback is mostly general in nature and refers to resulting performance measures such as flight path or hard landing [1], rather than to the trainee's control input patterns directly. Wouldn't it be nice if trainee pilots could get direct feedback on their manual control style, and compare it with that of veteran pilots, to see *how* they can improve rather than only knowing *what* they should improve?

Human pilot behavior and control have been researched for many decades, but the focus has been almost exclusively on creating pilot models for engineering applications, in particular predicting flight handling qualities and pilot performance [2, 3]. Although these models can be very effective in simulations replacing costly and time-consuming pilot-in-the-loop experiments, they are not very well suited to explain control style differences in a training environment. The main reason is that most models are based on control system theories such as classical control (transfer functions) and optimal control theory (including state estimation, biophysical models, and prediction).

Control-theoretical pilot models assume continuous operation depending on an uninterrupted feedback signal. Human pilots, on the other hand, have to get their information bit by bit from various sources ("scanning") that may have discrete perceptual thresholds. Human pilots have to allocate their attention and control efforts effectively to minimize workload. And most importantly: unlike a pure feedback controller, the pilot consciously makes intentional control inputs, and knows what effect his control input (approximately) will have on the (lagged) aircraft response. His self-consciousness and experience give him the ability to operate as a combined feedback and feedforward controller.

Trainee pilots obviously don't have the experience that a professional pilot uses to decide the feedforward part of his control, and are therefore mainly functioning as a feedback controller. However, trainee pilots are aware of their own control inputs, and with a few hints they could quickly develop a more advanced control style including feed-forward actions.

In the remainder of this paper we introduce early findings of observations and simulations of human pilots' manual control of the longitudinal aircraft motions. We will see how professional pilots, trainee pilots, and control models use the control stick (elevator deflection) control input differently to control the aircraft's pitch attitude effectively with the aim of following the intended flight path (i.e., level flight or tracking a glideslope). We will first show an overall analysis of trainee and veteran control input characteristics. Then we will zoom in and look at some details of the elevator control inputs.

Analysis of Control Frequency and Power using Spectrograms

More than 10 volunteering aeronautics & astronautics course students received casual basic flight training from a retired 747 captain in our fixed base Boeing 747-400 simulator (Fig. 1). We analyzed their stick (elevator) control inputs in a landing approach before, during, and after several weekly training sessions to see their progress. We also showed the trainees their own data in comparison with data we had obtained from the instructing captain pilot and from active professional pilots flying different Boeing aircraft. The analysis showing the clearest and easiest to understand differences in control style was a spectrogram analysis, of which a few samples are given in Fig. 2.

The simulated landing approaches started trimmed and on glide slope at ca. 600m (2000ft) altitude. The horizontal axis in Fig. 2 represents the flight time, with the red dashed line indicating the moment of touchdown. The vertical axis shows the period of the control input, from 0.5 to 14 seconds (first tick line at 2.0s). Lighter colors indicate lower control power, darker colors higher power.

Fig. 1: Fixed base Boeing 747-400 simulator at The University of Tokyo

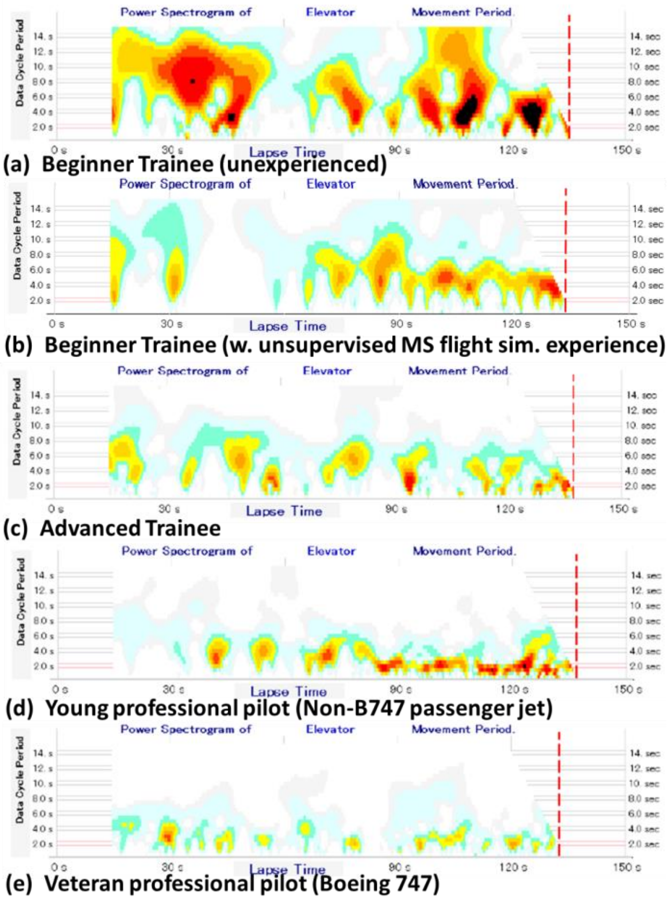

Fig. 2: Spectrogram analysis of control column (elevator) input during the last 2 minutes before touchdown (red dashed line).

The spectrograms in Fig. 2 show how the control style of beginning trainees is different from that of professional pilots. The professional pilots use much less control power and most of their control is of shorter period (higher frequency, 2~0.5s = 0.5~2Hz) compared to the trainees. This is in particular the case at the later part of the approach, probably because the relative impact of glideslope deviations gets larger when the aircraft gets lower and closer to the runway (resulting in both a need for more precise control and more salient visual cues). We also see that in a few weekly sessions am absolute beginner (a) is able to acquire basic manual control skills (c), with distinct main control inputs at a short period of about 2s. We generally see that beginning trainees with experience playing the Microsoft Flight Simulator game (b) have better performance in terms of flight path and less over-control, but still exercise relatively long period control at 4s and often even around 6 or even 8s.

As mentioned earlier, beginning trainees have little experience, and therefore have to rely mostly on feedback control. The large inertia and therefore slow response of a large aircraft, together with the double integration of the control input, will easily result in large overshoots, or even pilot induced oscillation (PIO), where the (trainee) pilot ends up spending more time on correcting his own over-control, rather than controlling the original flight path errors. We note that it is important to add some turbulence or an initial glide path deviation in the simulations when recording data for analysis, because otherwise the pilot may be able to keep the desired path with little or no control input.

A first step towards a better control style lies in not trying to control glide slope deviation directly, but controlling the more responsive aircraft pitch to a new reference value, and then waiting for the glide path to improve. The key to a stabilized approach, lies in a stabilized pitch attitude. Although maybe obvious to pilots, this is not trivial for trainees.

Changes in control frequency and power spectrum density with progressing training have also been reported by Ebbatson et al. [4]. They also explicitly note the outer (glide slope) and inner (pitch) control loops, and suggest that, particularly for large jet transport aircraft pilots, evaluation should include an assessment of their control input patterns because *"significant control input activity may not be reflected in large changes in the aircraft's attitude, and less so in the flight path. It is therefore unlikely that basic flight path measures alone will have the sensitivity required to investigate fine variations in manual flying skills [4]"*

Analysis of Damping Control from Time Histories

Even though the aircraft's pitch response is considerably faster than its noticeable change of glide path, a beginning trainee is still likely to over-control it and create large oscillations if relying only on visual pitch feedback information. It seems well trained and professional pilots are also using pitch-rate feedback to detect even the tiniest deviations from the desired reference pitch attitude. Together with that, they use their knowledge of the system's slowness and immediately after making a corrective control input, they move the stick back in order to prevent overshoot. This results in a high frequency control style, as shown in Fig. 3.

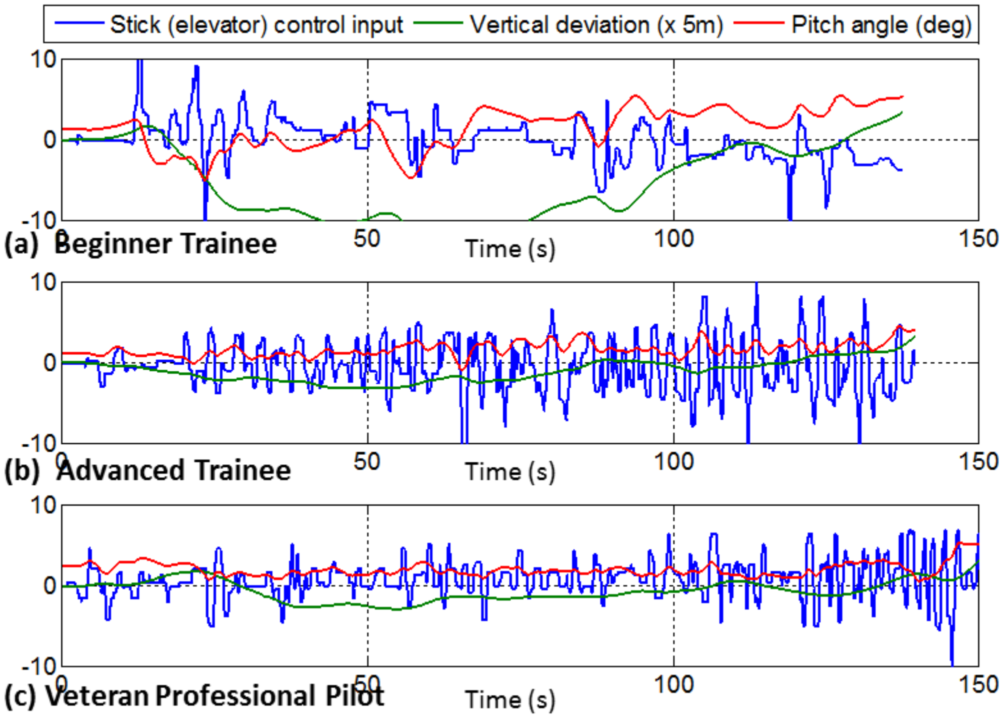

Fig. 3: Comparison of time histories

If we look closely at the control inputs of professional pilots, we often see that they don't make continuous block inputs, but that they make an initial large control input, immediately followed by a smaller or even reversed input (Fig. 4). There are several possible explanations of why this control style could help to stabilize the aircraft. One is that, whereas a small input may be sufficient, such a small input might be below or near the threshold of the input device, and therefore imprecise. A series of large amplitude pulses would average out to the same small input, but be more reliable. Another explanation could be that pilots are 'testing' the response of the aircraft, like online system identification or adaptive model predictive control tuning its own gain, before considering the following control input. Some pilots have mentioned to do so in particular before initiating the flare. Finally, the initial large amplitude control input will result in a quick response, while the following reduced or reversed input will provide some damping to reduce overshoot.

We verified this last idea with a small simulation, of which the result is shown in figure Fig. 5. All 4 input patterns have the same average stick deflection, but the half step and reverse (doublet) pattern inputs show a clearly faster response, with the reverse pattern reaching half of the pitch increase in 0.7s, whereas the continuous input needs 1.2s for that. The faster initial pitch response with subsequent damping enables the pilot to judge the effects of his control quickly and use it to consider his following control inputs. In actual flight the pilot is not continuously watching the pitch but also scans the other instruments. And even if he is continuously focusing on pitch control, his cognitive and neuromuscular lags would cause a delay of at least about 0.4s and probably more. Making slow continuous control inputs without timely confirmation of their appropriateness is therefore riskier than making fast but damped inputs.

Not all professional pilots make half –stepped or reverse (doublet) control inputs all the time. It seems that this type of control, and in particular the most extreme doublet variant, is more common towards the landing. Hess [5] and Gestwa [6] have also noted actual pilots don't make smooth, continuous but "pulsive" control inputs. The inputs presented by Gestwa may seem extremely spiky, but that is because he assumes an (Airbus-style) sidestick that produces a rate command instead of a (Boeing-style) yoke/stick that directly controls the elevator deflection angle. Daidzic [7] even suggests the reverse control pattern (a sharp pull, followed by a pushover of the yoke/stick) as the main control for the flare manoeuvre.

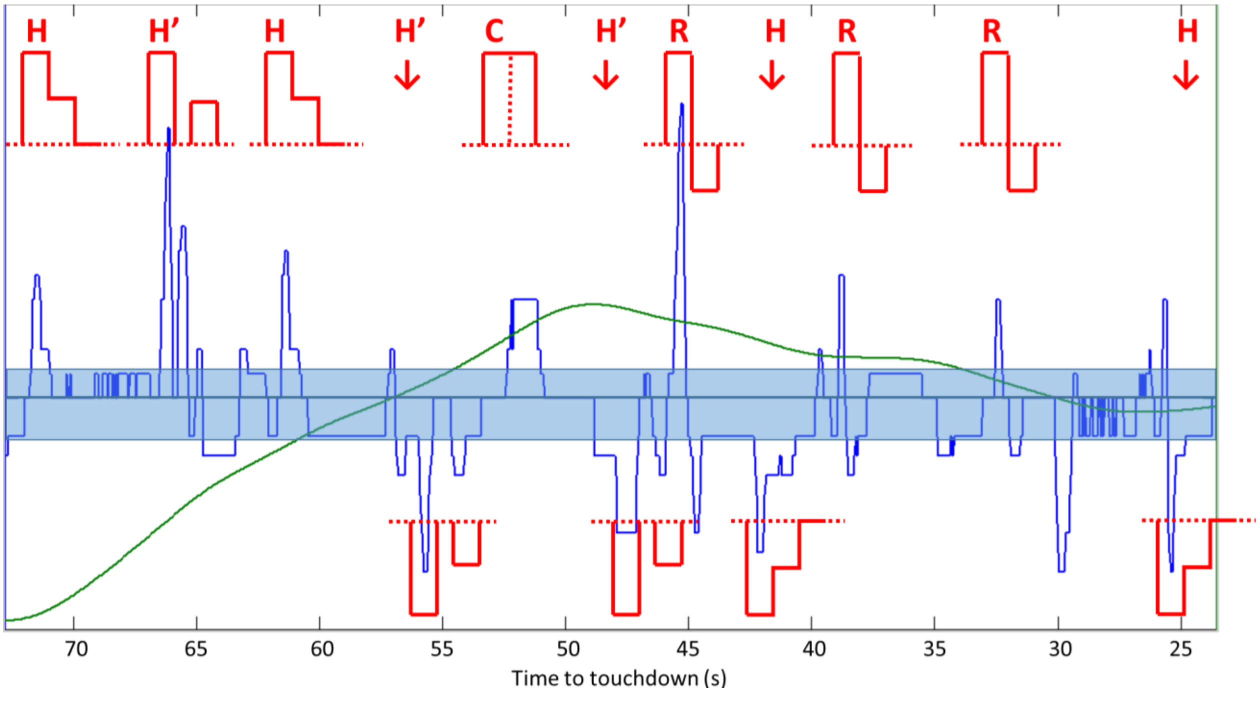

Fig. 4: Elevator control style of a veteran pilot. The blue line is the elevator control. The blue band shows the dead zone/noise level of the input device. Patterns are shown in red: C=continuous control (similar to trainee); H=half-step; H'=half step via zero; R=reverse (doublet) control. For reference, the vertical flight path deviation is also included (smooth green line).

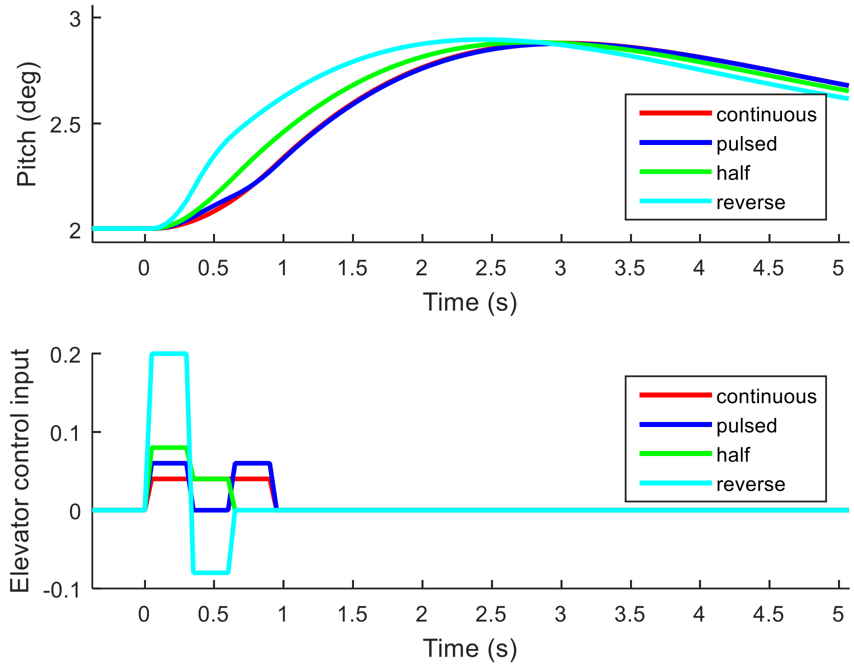

Fig. 5: Simulation of the effect of different stick (elevator) control input patterns on the aircraft pitch.

Landing Approach Simulation using Naturalistic Control

We are currently developing a simulation (Fig. 6) in Matlab Simulink to study the effects of different control input patterns in more depth. The simulation contains a longitudinal aircraft model based on the dynamics of a Boeing 747. From the aircraft states, the visual cues and main instrument information that the pilot uses during the approach are calculated. The parameters currently selected for feedback to the pilot are pitch, pitch rate, glide slope deviation, vertical speed, and the PAPI[1].

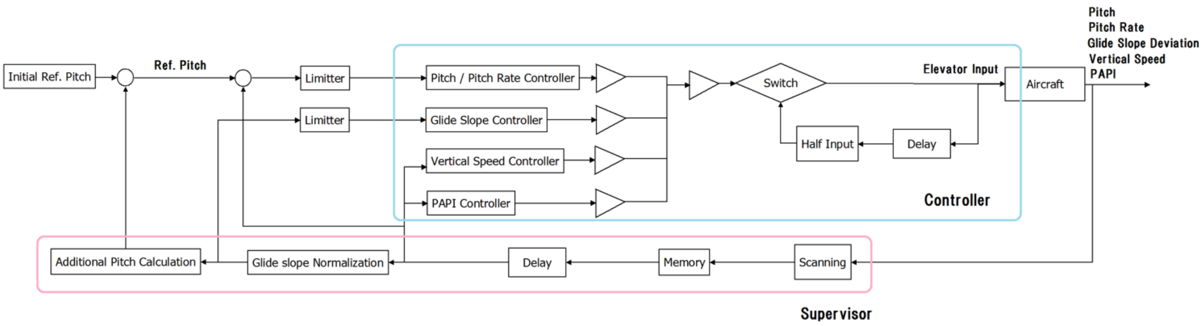

Fig. 6: Block diagram of the simulation

The pilot model part of the simulation contains the following elements:

- A supervisor part, observing the aircraft state and deciding a suitable reference pitch
  - A scanning model, switching from one parameter to the next, currently at fixed time intervals and in a fixed order.
  - A memory module, holding the last observed value for each parameter
  - A delay, modelling the time required for perception and information processing
  - A glide slope normalization function, because deviations at low altitude and close to the runway are considered more severe than same-sized deviations farther away.
  - A fuzzy-logic controller defining a reference pitch adjustment based on the normalized glide slope deviation
  - Limiters to reflect that small pitch, pitch rate, and glideslope changes are ignored
- A controller part

[1] PAPI: Precision Approach Path Indicator. A series of lights next to the runway that indicate in 5 levels whether the aircraft is (much) too high, on glide slope, or (much) too low.

- ➢ Basic elevator input calculation by a weighted average of 4 Fuzzy-logic controllers with pitch & pitch rate, glide slope, vertical speed, and PAPI as inputs.
- ➢ A switching module implementing half-stepped “pulsive” style control

This simulation was run with several settings, such as enabling or disabling the various feedback paths as well as changing between a continuous and the half-stepped control style. Fig. 7 shows an example of how pulsive control can stabilize the aircraft. In this case half-stepped control is assumed for the whole simulation. A choice of continuous, half-stepped, and reversed control depending on the flight phase and severity of the deviation might be more realistic, but would require an additional choice module that will be considered in future development. More details about the simulation and other results can be found in [8].

The development of natural style human control models and their evaluation in simulation can be useful to test our understanding of the principle control strategies that trainee and veteran pilots use. It can also provide insight in the relative importance of the various visual cues and information requirements for cockpit instrument design. Finally, fitting the model parameters to data obtained from real pilots or trainees can provide a basis for new analyses of differences in control strategy that are yet to be explored.

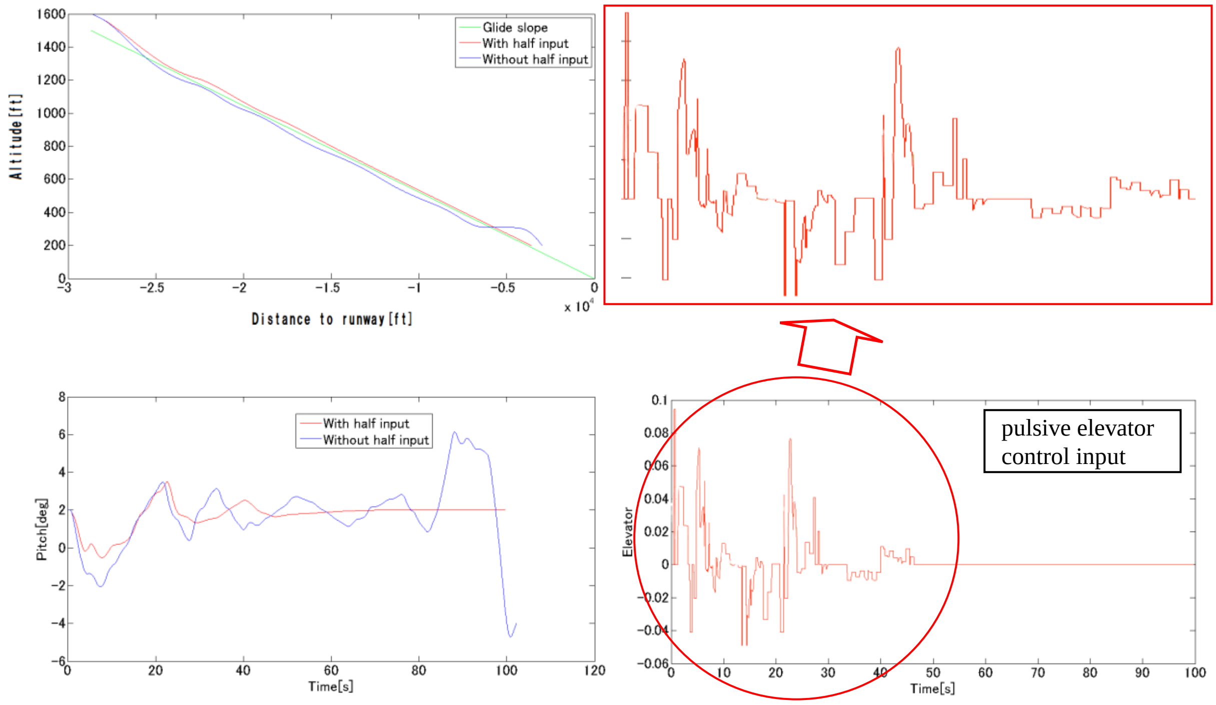

Fig. 7: Example output of human control simulation with (red) and without(blue) pulsive (half-stepped) control for a landing approach starting 30m (100ft) above the glideslope and without turbulence.

Conclusion

In this paper, we proposed a spectrogram analysis of longitudinal (elevator) control input to evaluate a trainee’s progress in the acquisition of manual flight skills. The spectrogram shows clear differences in control frequency and power between beginners, advanced trainees, and professional pilots.

We then showed that just a frequency analysis and continuous feedback models cannot capture all particularities of human control. Advanced trainees and professional pilots are seen to use a kind of pulsive control with large initial control inputs, followed by a lower or even reversed input. Our simulations confirmed that such a control style results in a quicker pitch response, while the flight path is not noticeably affected. This implies it is especially useful for the pilot’s inner loop control.

The presented control style differences may remain unnoticed in the traditional evaluation of pilots, which focuses mainly on the flight path. We implemented this control style in a naturalistic human pilot control model to further evaluate its effectiveness in closed-loop control with limitations on pilot response-time and cognition.

The results and analysis methods introduced in this paper provide a basis for objective, data-based instruction and evaluation of trainees and pilots. Detailed control style analysis could clarify the cause of control problems and support instructors' subjective feedback with visualized data and tangible recommendations. This would ultimately lead to more efficient training and more objective assessment of hand-flying skills.

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