Proceedings of the 12th International Symposium on Aviation Psychology
April 14-17, 2003, Dayton (OH), USA

TOTAL ENERGY-BASED PERSPECTIVE FLIGHT PATH DISPLAY FOR AIRCRAFT GUIDANCE ALONG COMPLEX APPROACH TRAJECTORIES

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Energy awareness and precise energy management become important during complex approach trajectories. To deal with this complexity the pilot's energy awareness can be increased by presenting him with explicit energy management information. The concepts of a so-called Total Energy Reference Profile (TERP) and 'energy angle' are defined in this paper and applied in the context of a perspective flight-path display. The resulting display presents aircraft independent energy management information fully integrated with the tunnel in the sky display and reveals five new and important energy cues. The design of the display is based on the Ecological Interface Design (EID) principles, supported by the Abstraction Hierarchy (AH) derived for the aircraft manual control task in (Amelink, van Paassen, Mulder & FLach, 2003). A preliminary evaluation shows that pilots can successfully fly approach trajectories using only the energy management information.

Introduction

Future approach trajectories will generally become more complex, consisting of multiple successive commanded speed and glide slope changes. In the companion paper (Amelink, van Paassen, Mulder & Flach, 2003), it is shown that the manual control of an aircraft speed and altitude is rather complex, as there exists no one-to-one coupling between the pilot control manipulators (elevator, thrust) and the pilot goals when flying an intricate trajectory (i.e. control the aircraft speed and altitude). Hence, a coordinated use of the aircraft controls is mandatory to achieve satisfactory levels of performance. Amelink et al. (2003) used the concept of e*nergy management* as the intermediating mechanism for flying the approach trajectory. An Abstraction Hierarchy (AH) was derived in which the energy principles underlying the potential pilot control strategies were structured. Based on the AH, information needs could be identified that might support pilots in becoming more aware of the 'energy state' of their aircraft, and also allow for clearer insight into how to actually 'manage' energy. That is, how to manipulate the aircraft controls to achieve the goals, satisfying all constraints.

In this paper, the lessons learned from deriving the AH are applied in an actual display design, using the principles of Ecological Interface Design (EID) (Vicente & Rasmussen, 1992). The goal of the present design is to augment an existing display, the tunnel-in-the-sky, with energy-relevant information in such a way that a pilot can directly perceive and act upon energy in a meaningful, task-oriented fashion. The paper is structured as follows. First it is shown how the various energy levels can be visualized. Then, the resulting 'energy display' and the ecological energy-related cues are discussed in detail. Third, the EID-related properties of the display are discussed. The paper concludes with a discussion of results from a first experimental evaluation.

Visualizing Energy

A tunnel-in-the-sky display is a modern primary flight display with a three-dimensional presentation of the trajectory to be flown (Mulder, 1999). Usually, the display is augmented with symbols like the flight path vector (FPV), which depicts the direction of the aircraft motion. The tunnel display has been chosen here as a basis for the energy information, because the perspective format already contains an important part of information about the commanded energy state. This will become clear below.

Expressing 'energy' a visual format

The concept of the energy display is based on predetermined speed and altitude profiles that define the approach trajectory. To visually express 'energy' it needs to be transformed into measures compatible with the tunnel display. A pilot is not very interested in the *exact* energy level of the aircraft, but rather in the energy *deviations*. This way the pilot can use the correction of energy deviations as the means for achieving the altitude and speed goals. As described above the pilot is first concerned with identifying the energy state deviations. Equations (1) and (2) give the expression for the potential energy deviation and the kinetic energy deviation:

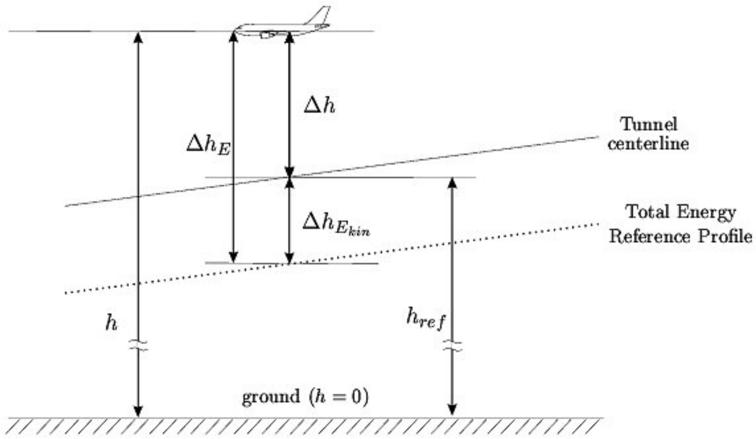

Figure 1. *The Total Energy Reference Profile is based the concept of expressing energy deviations in height.*

$$\Delta E_{pot} = W\Delta h \,, \tag{1}$$

$$\Delta E_{kin} = \frac{1}{2}\frac{W}{g}(V + \Delta V)^2 \,, \tag{2}$$

where W is the aircraft weight, Δh the altitude deviation, g the gravitational acceleration, V the aircraft speed over ground and ΔV the speed deviation. The zero wind condition is assumed here, i.e. the aircraft airspeed and groundspeed are equal. The sum of (1) and (2) is the total energy deviation:

$$\Delta E = \Delta E_{pot} + \Delta E_{kin} \,. \tag{3}$$

In the tunnel display the potential energy deviation is already present in the form of height; it is the aircraft vertical deviation from the tunnel centerline. The tunnel is actually the commanded potential energy profile. By expressing the other energy deviations relative to this height the energy representation can be completed, this is accomplished by dividing Equations (1) and (2) by the aircraft weight W. The result is the *kinetic energy deviation height*:

$$\Delta h_{E_{kin}} = \frac{\Delta E_{kin}}{W} = \frac{1}{2}\frac{(V + \Delta V)^2}{g} \,, \tag{4}$$

and the *total energy deviation height*:

$$\Delta h_E = \frac{\Delta E}{W} = h + \frac{1}{2}\frac{(V + \Delta V)^2}{g} \,. \tag{5}$$

When the approach trajectory is defined by an altitude and speed profile, the potential, kinetic and total energy profiles are implied. They are visualized by adding the perspective Total Energy Reference Profile (TERP) to the display. Figure 1 shows that the TERP is constructed by adding the *kinetic energy deviation height* to the commanded height (the tunnel centerline height h_{ref}). Some interesting properties can be noticed. First, the aircraft height above the TERP represents the (positive) total energy deviation. Second, the vertical separation between the tunnel centerline and the TERP is a representation of the speed deviation. Third, the perspective presentation of the TERP gives the pilot a *preview* of the future commanded energy states.

After having identified the energy deviations, a pilot is concerned with correcting them using elevator and throttle, controlling the energy rates. Again, the potential energy rate is already present in the tunnel-in-the-sky display: it is the vertical component of the FPV. The vertical flight path angle γ is the aircraft specific non-dimensional energy rate as derived by Amelink et al. (2003). Similarly, the total energy rate can be expressed in the energy angle γ_E :

$$\sin\gamma_E = \dot{E}_{sn} = \sin\gamma + \frac{\dot{V}}{g} \,. \tag{6}$$

In this equation, $\dot{E}_{sn}$ is the aircraft specific non-dimensional total energy rate and $\dot{V}$ is the aircraft acceleration along the flight path. For small flight angles the following relation can be used:

$$\gamma_E = \gamma + \frac{\dot{V}}{g} \,. \tag{7}$$

It expresses all energy rates in angles, which makes it compatible with the tunnel-in-the-sky display. Displaying the energy angle in conjunction with the already present FPV symbol reveals the three energy rates to the pilot. The energy presentation is completed by adding two elements to the tunnel-in-the-sky display: the TERP and energy angle symbol. Below the form of these elements is further defined.

Visual Form of Energy Representation

Total Energy Reference Profile. The TERP can be thought of as a “surface” that the aircraft should be on and the design reflects that. In Figure 2 the design of the TERP representation is shown. Lines (1) are the inner path lines, they coincide with the tunnel sides. Lines (2) are added texture marks and coincide with the lateral position of the tunnel frames. These marks should help the pilot judge the vertical distance between the tunnel and TERP (for perception of the speed deviation) and generate an optical texture gradient for better perception of the TERP. Lines (3) are the outer path lines and basically connect the endpoints of the texture marks to make it a more cohesive representation. This representation is defined to visually imply a surface while only using the space outside of the tunnel to avoid clutter in the center of the display. The result is a track type of representation.

Since the position of the TERP relative to the aircraft *and* to the tunnel produces important total energy and speed cues, respectively, the surface analogy is an important consideration. There are two optical invariants for judging the height above a surface: the optical splay angle and the optical depression angle (see (Mulder, 1999) for a comprehensive discussion of these cues in the context of tunnel-in-the-sky displays). The TERP is designed to include both optical invariants (Amelink, 2002).

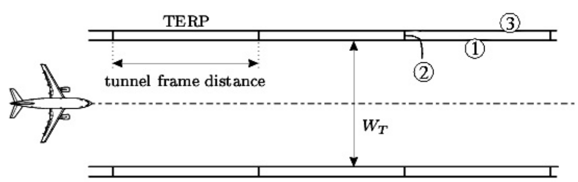

Figure 2. *Visual design of the TERP: (1) and (3) are the path lines, (2) the texture marks and W_T indicates the tunnel width.*

Energy angles. The way in which the flight angles are represented by symbols in the display is shown by Figure 3, in the display the vertical distances between the symbols and the horizon represents the angles. The form of the symbol is a long horizontal line with a gap in the middle to prevent overlap with FPV symbol. Since the energy angle does not have meaning in the lateral plane the line is always parallel to the horizon and the gap is always aligned with the flight path vector. The line needs to be long in order to have an overlap with the TERP. This can best be seen in Figure 6, where (14) represents the energy angle which overlaps the TERP (13).

Energy cues in the tunnel display

Figure 6 shows the resulting display. Two energy elements have been added to the existing Tunnel-in-the-Sky display to indicate the energy levels and the energy rates. The integrated format of the tunnel, flight path vector, the TERP and the energy angle contains five important new cues for the manual control task. The cues show energy deviations and the means to correct them. Amelink et al. (2003) state that the throttle directly controls the energy angle and the elevator directly controls the vertical flight path. In other words, the energy angle symbol and the flight-path vector symbol are manipulated with throttle and elevator, respectively.

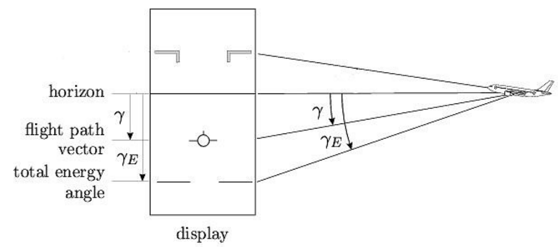

Figure 3. *The display symbols representing angles.*

Total Energy Level Deviation Cue. The aircraft vertical position relative to the TERP indicates the total energy deviation. When such a deviation occurs, the *throttle* is the control to correct it. Figure 4 shows that the deviation can be perceived through the splay angle error. The middle picture shows that for zero deviation the aircraft is right on top of the TERP, which is then perceived as a horizontal line.

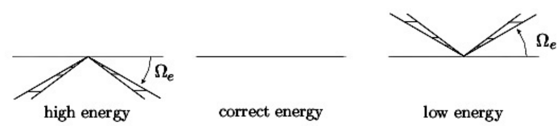

Figure 4. *The deviation from the TERP can be perceived through the splay angle error Ωe.*

Energy Rate Cue. The total energy rate is expressed in the energy angle, which is defined relative to the horizon. When the energy angle is above the horizon there is a total energy *increase*, when it is below the horizon there is a total energy *decrease*. The energy angle also represents the "energy flight path" to the TERP. Figure 5 shows that when there is an overlap between the long line of the energy angle symbol and the TERP the total energy is converging to the commanded total energy level.

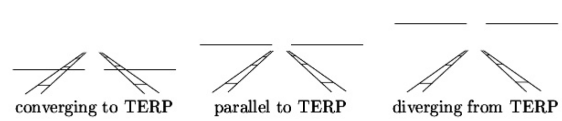

Figure 5. *The intersection of the energy angle symbol and the TERP in the display indicates the point of interception of the TERP in the future.*

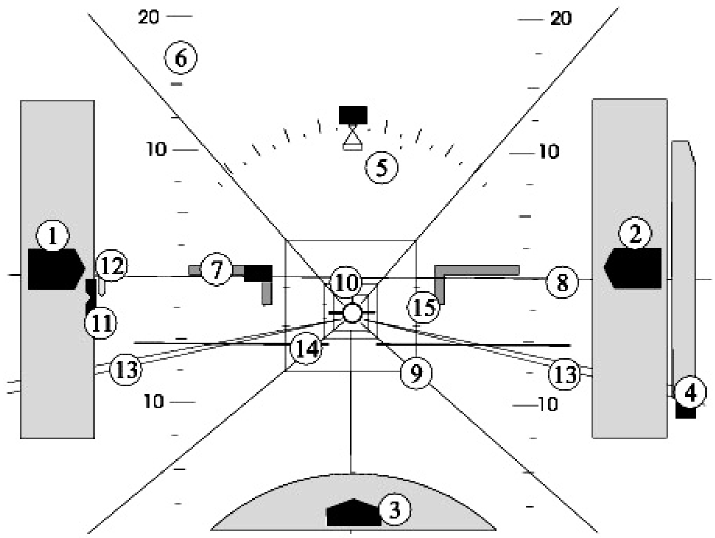

Figure 6. *Symbols found in the Energy-augmented Tunnel Display: (1) speed tape, (2) altitude tape, (3) compass, (4) vertical speed indicator, (5) bank angle and slip indicator, (6) pitch ladder, (7) aircraft symbol, (8) horizon, (9) perspective tunnel, (10) flight path vector symbol, (11) speed bug, (12) speed trend vector, (13) perspective TERP, (14) energy angle symbol and (15) speed marks (Amelink, 2002).*

Acceleration Cue. Equation (7) shows that the energy angle is the sum of the vertical flight path angle and the non-dimensional acceleration. Thus the difference in angle between the energy angle and the flight path vector expresses the *acceleration along the flight path*. Note that it is possible to generate accelerations along the flight path with the elevator control, controlling the FPV, *and* the throttle control, controlling the energy angle. This cue is also important for finding and maintaining steady flight.

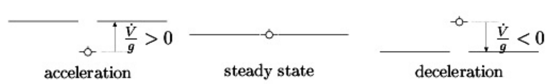

Figure 7. *The energy angle and the flight-path vector generate the acceleration cue.*

Potential Path Cue. This is an important cue of the energy display because it directly links the throttle setting to the commanded flight path: it lets the pilot set the throttle *independent* of the momentary flight path angle and speed in a very direct way. The energy angle shows the vertical flight path angle that the current throttle setting could sustain at the current speed. When stabilized the energy angle has to match the direction of the future tunnel trajectory, Figure 8 shows how the display depicts this visual cue.

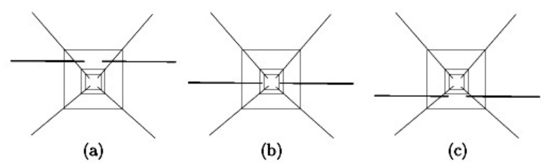

Figure 8. *Energy angle and tunnel show the throttle setting for a steady flight path (a) too much, (b) correct setting and (c) too little.*

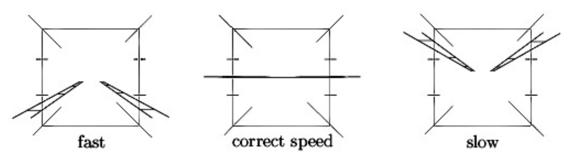

Figure 9. *The vertical separation between the tunnel center and the TERP is the aircraft speed deviation expressed in height*

Speed. As described above, the aircraft speed deviation is represented by the vertical separation between the tunnel and the TERP. This distance, the kinetic energy deviation expressed in height h_{KE}, is the cue for speed deviations, independent of the aircraft position relative to the tunnel. When the speed is right, the total energy error and the potential energy error are the same and so is the aircraft height above the tunnel centerline and the TERP. Due to this property, the allowable speed deviations can be projected on the tunnel sides by the speed marks shown by (15) in Figure 6 and Figure 9. These marks show the allowable vertical separation between the

TERP and the tunnel centerline. The TERP has to be in-between the marks at the location of the aircraft to be within the allowable speed margins.

Working with the Cues

How the cues are exactly used during flight can only be evaluated experimentally. However, the following can be said based on discussion with pilots and the analysis of the task (Amelink et al., 2003). The task of piloting can be split into *long-term* control and *short-term* control. The short-term control is concerned with the immediate response of the aircraft used to correct deviations and to follow the flight path and speed profile. Long-term control is what pilots call stabilizing. It is concerned with balancing the forces that act on the aircraft so that it will naturally fly at the commanded speed and vertical flight path angle in steady state. The cues in the display present information to the pilot that facilitates both parts of the control task.

Short-term control. For short-term control the deviation from the commanded energy state should be directly perceived. The aircraft position relative to the tunnel centerline is the cue for the potential energy deviation. In the same way the aircraft position relative to the TERP represents the aircraft total energy deviation. Now, there are four possibilities. First, the aircraft is on the tunnel centerline and on the TERP. This represents the commanded energy state and there is no need for corrections. Second, the aircraft is on the tunnel centerline but not on the TERP. In this case there is not a potential energy error and the kinetic energy deviation equals the total energy deviation. To correct the total energy error the pilot must use the throttle. Third, the aircraft is on the TERP but not on the tunnel centerline. There is not a total energy deviation but a energy distribution deviation. The kinetic and potential energy deviation are equal but opposite. Elevator control should be used to correct the deviation. Fourth, the aircraft is on neither the tunnel centerline nor the TERP. Both total energy and energy distribution deviations occur. Both throttle and elevator are needed to correct the deviations.

In all cases the pilot will use feedback from the energy angle symbol and the FPV symbol to control the energy rates with throttle and elevator. They show the angles at which the TERP and tunnel will be intercepted, allowing pilots to precisely select the control inputs to correct the deviations but also trim energy rates for the long-term control.

Long-term control. Matching the energy rates to the commanded flight path and speed is the key to stabilizing the aircraft. When stabilizing, the energy angle is used in conjunction with the tunnel to determine the stabilized throttle setting; the energy angle should be aligned with the future tunnel center (see Figure 8). To fly down the tunnel the FPV symbol should also be aligned with the tunnel, which implies that the energy angle and FPV symbol are aligned during stabilized (i.e. steady) flight. This correlates with the acceleration cue shown in the center figure of Figure 7; speed is constant thus the acceleration along the flight path is zero.

Preview. A very important aspect of the energy display is that it provides a preview of the future commanded energy state. The pilot can actually see if the stabilized condition will take the aircraft to the commanded future energy states. This should result in better anticipation and a reduction of the overall pilot control gain. The other advantage of a preview is that the pilot can see a commanded change of path or speed well in advance. Figure 10 shows the two types of changes that can be encountered. A speed change, as (a) shows, can always be recognized by the upcoming vertical separation of the tunnel and TERP. A flight path change can always be recognized by the equal change of TERP and tunnel shown by (b). These changes could also take place simultaneously and the display will still show the pilot a valid energy representation but such a change lacks the power of recognition of familiar situations. The energy display offers a preview of and guidance for future energy states and should support approaches along complex trajectories.

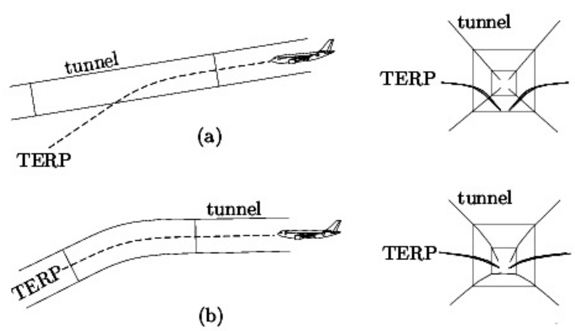

Figure 10. *The preview of (a) a commanded deceleration and (b) a commanded descent.*

EID-related Properties of the Display

Ecological Interface Design (EID) (Vicente and Rasmussen, 1992) is a theoretical framework for designing interfaces for complex human-machine systems. It is the approach to interface design that gives priority to the worker's environment, concentrating on how the environment imposes constraints on the worker. It is based on the three levels of the Skills, Rules and Knowledge (SRK) taxonomy. A display based on the EID principles should support the operator on all three levels of cognitive processing. How the three levels are supported in the energy display is listed below.

SBB is based on time-space 'signals' that can be directly used for control. The five cues discussed above all represent signals, and they are all compatible with SBB. This can be illustrated by the following: When a hypothetical pilot is completely unaware of the energy constraints he should be able to fly the approach just by keeping the energy angle on the TERP with the throttle and the FPV symbol inside the tunnel with the elevator. This is a skill-based tracking task with a low cognitive load.

RBB is based on the perception of 'signs' in the work domain that trigger a set of previously stored rules for dealing with a familiar situation. The two expected changes are speed and glide slope changes. Since the perspective trajectory gives a preview of the future commanded energy state, the pilot should be able to recognize which of the changes is coming up and act on it without reasoning.

KBB is based on the perception of 'symbols' that carry meaningful information in the work domain used for unanticipated situations and problem solving activities. The visualization of the energy constraints is based on the top three levels of the abstraction hierarchy (Amelink et al., 2003) and should allow for reasoning and problem solving. The visualization does *not tell the pilot what to do but it shows the structure of the energy constraints revealing possible solutions*. The pilot is allowed to choose any control strategy that satisfies the system goals. This will result in a naturalness of control that is not available from interfaces based on a more conventional, procedural task analysis.

Results of a Preliminary Evaluation

The preliminary evaluation took place in a fixed base flight simulator using the flight model of a Cessna Citation 500, a small twin-engine jet. The goal of the evaluation was to get a feel for how experienced pilots would deal with energy information and the perspective path representation. The energy display was presented without the speed bug and without the speed trend vector to force the subjects to use the energy representation. Subjects needed a much longer period for familiarization then anticipated. On the whole, they successfully managed to fly the approach trajectories using the energy management information, but it was clear that they would not (yet) outperform a more conventional tunnel-in-the sky display augmented with a speed bug and speed trend vector. The subjects did comment, however, that their energy awareness increased with the energy display.

Final Remarks

The energy display is the result of a comprehensive study of the energy constraints in flight using the abstraction hierarchy and EID principles (Amelink, 2002). Whether the contributions of the EID design are beneficial in terms of the 'common' metrics like pilot performance, workload and situation awareness, is unclear and needs to be investigated through an extensive pilot-in-the-loop evaluation. We believe, however, that also other 'metrics' should play a role in the evaluation of our concept. An example could be the amount of coupling to the levels of the SRK taxonomy and to the levels of the Abstraction Hierarchy, along the philosophy advocated in Yu, Lau, Vicente & Carter (2002).

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A demonstration version of the energy display can be downloaded from:
http://www.amelink.net/mscthesis