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APPLYING THE ABSTRACTION HIERARCHY TO THE AIRCRAFT MANUAL CONTROL TASK

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One of the most difficult aspects of manually controlled flight is the coupling between the control over the aircraft speed and altitude. These states can not be changed independent of each other through the aircraft control devices, the elevator and the throttle. Rather, to effectively change an aircraft's speed and altitude, the controls have to be coordinated. The mediating mechanism that underlies the coordination of the controls is the management of the aircraft's energy state. This paper shows that the Abstraction Hierarchy framework can be effectively used to gain more insight into the underlying structure of the aircraft energy management problem. The derived AH representation is based on the analysis of the energy constraints on the control task and the pilot's way of dealing with these constraints. It reveals the levels of abstraction that are necessary to link the aircraft's physical controls to the speed and altitude goals and also how the aircraft energy is a critical mediating state of the control problem.

Introduction

Langewiesche (1944) describes the art of flying in his famous book "Stick and Rudder". This book was one of the first attempts to accurately describe flying and is still valued among pilots, engineers and psychologists. Langewiesche puts a lot of emphasis on what he calls "lift". This is not the 'lift force' generated by the wings as analyzed in aerodynamics and aeronautical engineering, but he uses it to illustrate an aircraft's "potential to fly". He writes that an aircraft with lots of "lift" is safe because the aircraft can easily gain altitude or pick up speed, while an aircraft with a lack of "lift" is very limited in maneuvering.

In this paper, Langewiesche's "lift" is equated to *total energy*. More total energy provides greater "potential to fly." In other words, the opportunity to *exchange* kinetic energy (speed) and potential energy (altitude) provides room for maneuvering. Thus, flying skill depends on energy awareness and energy management. The aircraft manual control task involves controlling the energy state of the aircraft.

This paper will explore Rasmussen's (1986) Abstraction Hierarchy (AH) as a framework for mapping out the energy constraints. A companion paper (Amelink, van Paassen, Mulder, and Flach, 2003) applies the lessons learned in this paper to represent energy in the primary flight display. By mapping the energy constraints to the pilot interface the AH can become an *externalized mental model* (Vicente & Rasmussen, 1992) to enhance pilot energy awareness and energy management.

Structuring the Control Problem

Flach, Jacques, Patrick, Amelink, van Paassen, and Mulder (in press) presented an early attempt to represent the role of energy structured in the AH framework. In this representation the energy constraints were represented on the second level of the AH, the "abstract function" level. On the first level of the AH, the "functional purpose" level, the goal was defined as "safe flight". On the third level, the "general function" level, the representation showed the cause-effect relations between the aircraft variables. Flach et al. (in press) referred to this as an 'evolving image' and it was used in this paper as a starting point to further elaborate the role of the energy constraints.

System boundaries

The top level of the abstraction hierarchy, the "functional purpose" level, defines the system's goal in the environment. A precise definition of the system boundaries will lead to a better insight into the system that is being analyzed. Our interest is the role of energy during the precision landing task and the system goals and boundaries should reflect that. There are basically two goals that the pilot has during (symmetric) flight: maintaining a certain speed and altitude. Between these stationary states, the reference levels for speed and altitude can change along the approach, resulting in speed and altitude profiles. This is the pilot's main concern in the precision landing task studied here. Of course, other tasks, like managing the fuel systems, are needed for the aircraft to function as a whole, but these are left out of consideration in this paper. Thus, the "functional purpose" level is defined by speed and altitude profiles that need to be flown. For the ease of discussion let us assume that the flight is along a predefined approach trajectory like an ILS glide slope and that the altitude and speed profiles are predetermined.

On the other end of the abstraction hierarchy we find the aircraft-dependent levels: "the physical form" level and the "physical function level". These levels deal with the physical implementation of the aircraft system. On these levels are, amongst other things, the manipulators the pilot has for the control of symmetric flight: the throttle and elevator. The coordination of these controls to achieve the speed and altitude goals is one of the main points of interest for Langewiesche: the student pilot has a throttle and an elevator to control speed and height, but which manipulator controls what? The answer is that *neither one controls the aircraft speed or altitude independently*, they must be used in coordination. As mentioned earlier, the key to the coordination of the manipulators lies in controlling the energy state of the aircraft and this is what should be on the middle levels of the AH. This level links the means (throttle, stick/elevator) and the ends (target speeds and altitudes) using energy relations. Explicitly representing these links is a primary goal of ecological interface design (Vicente, 2002). These links must also be addressed in the design of automatic flight control systems (Lambregts, 1983).

Control Task Analysis

Pilot control strategies

During the approach the pilot manages the aircraft state in order to comply with the speed and altitude goals set by a predetermined trajectory. The pilot has two goals: first, to stay on the approach path or glide slope, and second, to maintain the right airspeed. Atmospheric disturbances will interfere with accomplishing these goals and will lead the pilot to take corrective actions. Depending on the type of aircraft and landing situation, the pilot will generally apply one of two control strategies. In the first control strategy, the pilot uses the throttle to control the vertical flight path (altitude) and the elevator to regulate speed (pitch-to-speed). In the second control strategy, the pilot uses the elevator to control the vertical flight path and the throttle to control speed (throttle-to-speed). These reflect two different coordinative structures (Bernstein, 1967), in terms of which degrees of freedom are "locked-out" and which degrees of freedom are "controlled." In principle, either strategy might be used to land. However, there seem to be clear preferences. The "pitch-to-speed" mode seems to be preferred for standard runway approaches (e.g., commercial aviation), while the "throttle-to-speed" mode seems to be preferred for approaches to shortened runways (e.g., aircraft carriers). The focus of the present analysis will be on a landing to a standard precision runway, which is typical for commercial and general aviation. The analysis is limited to the zero-wind condition.

The energy controls

To understand the aircraft energy control one must first understand *what* the energy relations are and *how* energy can be regulated. The energy state of the aircraft is defined by its kinetic and potential energy. Kinetic energy is the energy of a moving object and is a function of its speed as shown by:

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

where W is the aircraft weight, g the gravitational acceleration and V the aircraft's velocity relative to the ground. The aircraft's potential energy is determined by its altitude above a ground reference such as the runway threshold, as shown by:

$$E_{pot} = Wh , \qquad (2)$$

where h is the altitude above the reference.

The sum of these two energies is the aircraft's total energy. In physics, the law of conservation of energy states that energy cannot be created or destroyed. This means that when the total energy is constant, the kinetic and potential energies can change but only in equal and opposite amounts. Thus altitude can be traded for speed and vice versa without gaining or loosing total energy. Langewiesche is making this point where he describes that "speed = height" and calls it the "law of the roller coaster". The other implication of the law of conservation of energy is that an aircraft can only *lose* total energy through drag: the aircraft's energy is transformed into heat, which is bled off to the surrounding air. The only way in which an aircraft can *gain* total energy is through the energy added by the engine. The net total energy flow into the aircraft is a function of the difference between engine thrust and drag as shown by Equation (3):

$$\frac{\dot{E}}{V} = T - D , \qquad (3)$$

where $\dot{E}$ is the total energy rate, T the engine thrust force and D the aircraft drag. We can assume drag to vary only in the long term and since the throttle controls the engine, the throttle becomes the aircraft's energy control. Thus, the throttle does not control speed or altitude like the control strategies imply but rather controls the aircraft's *total energy rate*.

What does the elevator do? Let us assume that the elevator does not produce any appreciable drag when deflected, and that the aircraft maneuver rates are small so that an almost constant drag can be assumed. Since the elevator produces neither drag nor thrust it cannot control the total energy level. What it does do is *exchange* energy between kinetic and potential energy: it is the energy distribution device. This is where Langewiesche's "law of the roller coaster" comes into play: when using only the elevator to go up it will be at the expense of speed; in a complimentary fashion, speed can be gained at the expense of height.

The reservoir analogy

The throttle and elevator as energy controls can be visualized as if the aircraft is a system holding two reservoirs. One contains the kinetic energy and the other the potential energy. Together these reservoirs represent the total energy. There is one energy flow into/out of the system; it is the energy flow resulting from the difference between thrust and drag as shown by Equation 3. This flow is then distributed over the kinetic and potential energy flows into/out of the reservoir. The throttle can be seen as a valve regulating the total energy flow into the system and the elevator can be seen as a valve distributing the energy flow. Figure 1 is a graphical representation of the analogy, showing the energy flows (the arrows indicate positive flows).

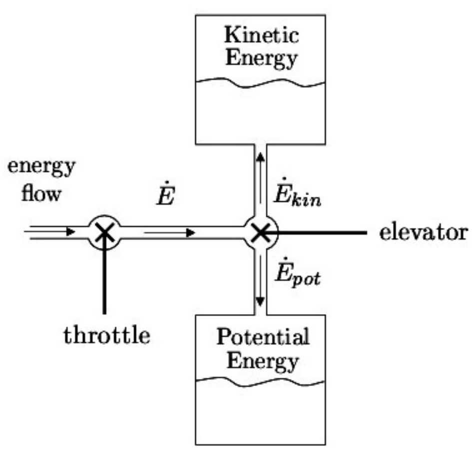

Figure 1. The r*eservoir analogy. The throttle regulates the total energy flow and the elevator controls the energy flow distribution. In this Figure,* $\dot{E}$ *,* $\dot{E}_{pot}$ *and* $\dot{E}_{kin}$ *represent the total energy rate, potential energy rate and kinetic energy rate, respectively.*

Energy awareness and energy management

The pilot acts on the energy state of the aircraft. However, he can only do this effectively if he can identify the energy state. Most pilots have a gut feeling about this, based on their experience and feel safe when they have lots of energy. They will avoid low energy states because the lower energy boundaries are deadly. Insufficient kinetic energy means that the aircraft is moving too slow and is close to a stall. A lack of potential energy means that the aircraft is dangerously close to the ground. The combination of low and slow is especially dangerous because the pilot no longer has the freedom to quickly pull up and gain altitude at the cost of speed in order to avoid obstacles, or to dive and quickly pick up speed in order to prevent a stall. The pilot likes to be fast and high, when he has lots of energy to exchange for safe maneuvering. This is a rudimentary form of *energy awareness*. When the pilot is flying a precision approach he will have to be able to identify the energy state more precisely in order to use the energy controls to correct deviations from the speed and path goals.

The goals have been defined as altitude and speed. When the pilot is confronted with deviations from the commanded altitude and speed he will somehow have to translate those deviations into actions to be taken in terms of energy. This translation can be made by referring to the energy state matrix in Figure 2. The matrix shows the possible energy state deviations of the aircraft. On the vertical axis the total energy deviation ΔE is the sum of the kinetic ΔE_{kin} and potential energy deviations ΔE_{pot} on the horizontal axis. Each cell of the grid represents a state deviation from the reference state defined by the total, kinetic and potential reference energies: E_{ref} , $E_{pot_{ref}}$ and $E_{kin_{ref}}$ respectively. Line B is the line of zero total energy error, cells on this line have the proper total energy but the distribution of the total energy over kinetic and potential energy may be inadequate. The solution to the 'problem' is an exchange of energy that can be realized by using the elevator. Line A is the line of zero energy distribution error; cells on this line have the proper *ratio* of kinetic and potential energy but may have a total energy error. These deviations can only be corrected by increasing or decreasing the total energy using the throttle.

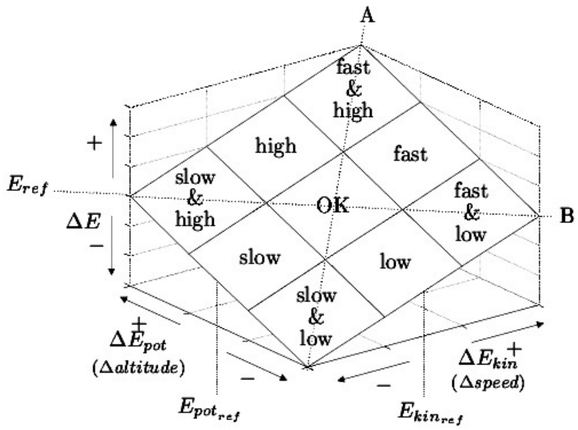

Figure 2. *The energy state matrix translates speed and altitude deviations into energy deviations.*

Cause-effect relation of pilot controls and goals

Of course, an aircraft does not have valves that control energy. Energy control is an abstract view of the control problem. In this section a closer look is taken at how the energy relations are represented in the physical cause-effect relations between the controls and the goals. Amelink (2002) presents a diagram that shows how the controls affect the goals through the relevant state variables. The diagram is simplified in Figure 3 to show only the most relevant relations for this paper. The arrows represent the cause-effect relations between variables; how one leads to the other. It is important to realize that the arrows do *not* represent energy flows or forces. There are three main areas of interest indicated by A, B and C. A shows how elevator inputs directly control the vertical flight path angle γ and the altitude. B shows how throttle inputs lead to speed after passing through box C. Box C represents the energy relations and forms the most important link between the direct elevator control path (box A) and the direct throttle control path (box B). The other link is through the dashed arrow, which represents the aircraft's pitching tendency due to thrust changes. The latter is an important aircraft characteristic that determines the preference for either control strategy but it is not part of the energy coupling, its implications are discussed at the end of this section.

Our main interest is in the role of the content of box C. Again the law of conservation of energy tells us that the energy rates must add up. The total energy rate is the sum of the potential and kinetic energy rates as shown by Equation (4):

$$\dot{E} = \dot{E}_{pot} + \dot{E}_{kin} \ . \qquad (4)$$

In box C the relations are drawn for a conventional generic aircraft. Because the thrust acts more or less along the flight path it will first of all accelerate the aircraft thus the total energy added to the aircraft 'wants' to become kinetic energy. This is represented by the arrow connecting $\dot{E}$ and $\dot{E}_{kin}$. However, the elevator can be used to achieve a certain vertical flight path angle that is directly related to the potential energy rate. In other words: the elevator is used to demand a certain amount of potential energy rate. The kinetic energy rate is a result of the total energy rate minus the demanded potential energy rate. This is what the arrows in box C represent. Again note that they do not represent energy flows but cause-effect relations.

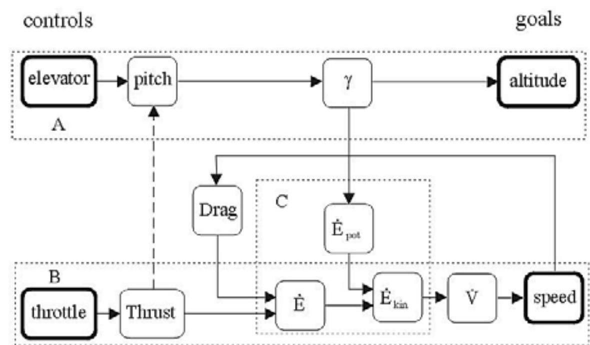

Figure 3. *Cause-effect relations between the aircraft control manipulators and pilot's goals, characterized through the main aircraft symmetric state variables.*

In large transport aircraft the total energy will tend to become kinetic energy because the coupling represented by the dashed arrow is usually weak. However, small trainer aircraft have a much stronger coupling and have the characteristic to pitch up when throttle is applied. Thus the throttle has a direct effect on the vertical flight path and the potential energy demand in the same way that the elevator does. In the reservoir analogy the throttle also partly operates the distribution valve. For these aircraft the 'throttle to path and elevator to speed' strategy is preferred.

Short-term and Long-term control

Amelink (2002) splits the control task into two parts. The first part is concerned with the correction of the state deviations and is referred to as *short-term* control. The controls are used for their direct effect as represented in Figure 3. Once the state deviations are corrected the pilot will want to trim the aircraft, creating a steady flight condition at the commanded flight path and speed. This is the second part of the control task that pilots call "stabilizing the aircraft" and it is referred to as *long-term* control. The controls are no longer used for direct control but their settings have to be found that leads to the desired steady flight condition. By definition the speed is constant in steady flight. In Figure 3 this means that the kinetic energy rate has to be zero and that the total energy rate and potential energy rate must be equal (see Equation (4)). It also means that the throttle has to be set to comply with the commanded vertical flight path angle. For long-term control the throttle and elevator need to be coordinated such that the elevator controls the vertical flight path and that the throttle is used to match the total energy rate to the potential energy rate demand. Short-term control is concerned with controlling the energy levels and long-term control is concerned with controlling and matching energy rates.

An Abstraction Hierarchy for Aircraft Energy Management

The above analysis allows us to fill in the second, "abstract function" and third, "general function" levels of the AH. Figure 4 shows the content of each level related to the associated part of the analysis. The names of the levels of the AH are adopted from (Rasmussen, Pejtersen, & Goodstein, 1994) and their content become:

(1) <u>Functional purpose</u>: The system's meaning to the environment. The goal of the aircraft, in the light of the manual control task is to follow the altitude and speed profiles.

(2) <u>Abstract function and priority measures</u>: The energy relations govern the aircraft's movement in the vertical plane. This level describes the energy laws that the aircraft's motion has to obey and centers on the law of conservation of energy. The speed and altitude goals are expressed in energy goals. In order to satisfy the goals on the level above, the energy goals have to be satisfied.

(3) <u>General function and work activities</u>: These are independent of the physical implementation. This level contains energy awareness and energy management. The throttle is the aircraft's total energy control and the elevator is the energy distribution control, control over energy rates gives control over the energy levels (the aircraft energy state) that has to satisfy the level above.

(4) <u>Physical function and processes, equipment functioning</u>: This level is dependent on the physical implementation of the system. The above levels hold for a generic fixed wing aircraft, they are independent of the type of aircraft. On this level the cause-effect relations of the aircraft specific characteristics become important. Examples of these characteristics are the pitching due to throttle control (the dashed line in Figure 3) and drag variation with airspeed.

(5) <u>Physical form and configuration</u>: This level contains a description all aircraft components. It is highly aircraft-specific and is not further discussed.

The AH has a number of important properties. First of all, each level is a representation of the complete system under consideration. The level of abstraction determines the 'view' on the system and results in a set of terms, concepts and principles unique to that level. The relation between the levels is described by Rasmussen et al. (1994) as the *why-what-how* relation. Each level has this relationship with its adjacent levels. For example, looking at the "general function" level we find energy awareness and energy management. The reason for energy management is defined one level higher, on the "abstract function" level. How the energy is controlled is through controlling the right state variables described on the "general function" level. The upper levels of the AH describe the goals and the lower levels describe the means available to achieve these goals.

The derived AH is not the abstraction-decomposition space as described by Rasmussen et al. (1994). Structural decomposition of the energy constraints does not seem to be possible in the same way as is done for process control plants. The difference is found in the nature of the domain; because the energy constraints do not consist of subsystems like complex plants do. In the case of the energy constraints the interesting part we are after is the functional abstraction of the chain of the means-end relations that connects the physical control inputs with the goals of the pilot.

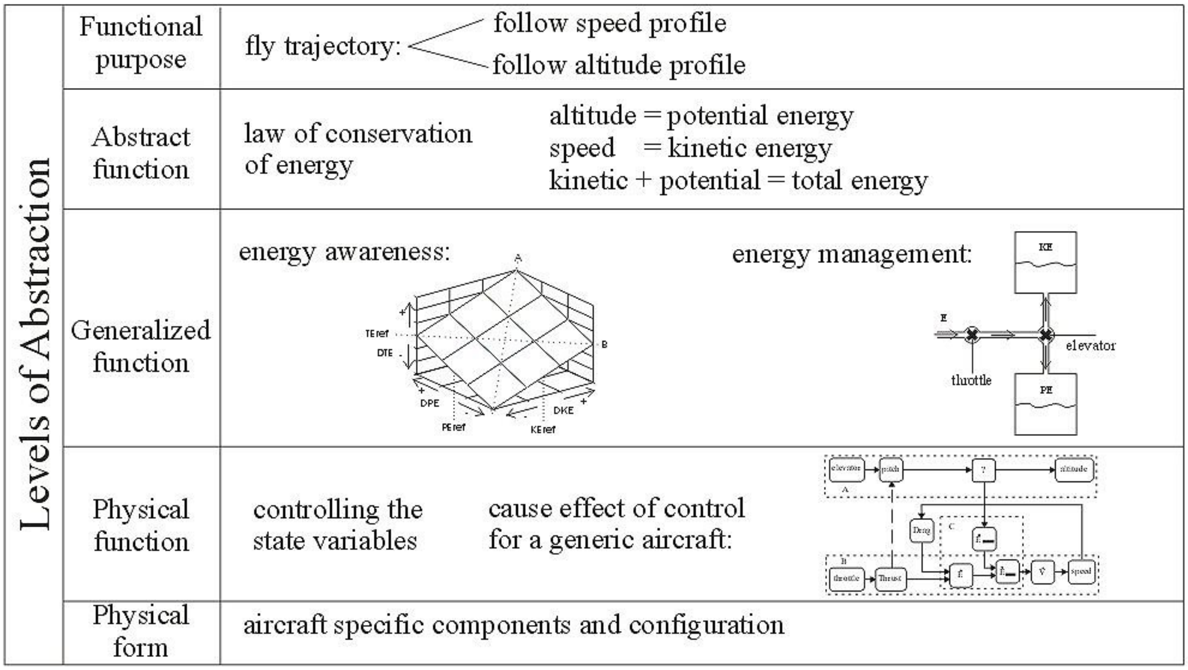

Figure 4. *The Abstraction Hierarchy (AH) for the energy constraints on the aircraft manual control task.*

Conclusions

The derived AH is a representation of the energy constraints as a subset of the complete aviation work domain. It can serve as a externalized mental model that an experienced pilot has for symmetric aircraft control. As Vicente and Rasmussen (1992) state, the AH can only represent what the designer, researcher or expert knows. It has not come up with answers about the energy constraints that were unknown but the AH framework has helped to structure the process of analyzing the control task. It enabled us to ask the right questions about the work domain and structure it in a psychologically relevant way that supports the mapping of goal-directed behavior.

The next step is the actual design of a display to present the energy information to the pilot. The AH is part of the Ecological Interface Design framework applied to the design of the energy display described by Amelink et al. (2003).

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