X A Search for Meaning: A Case Study of the Approach-to-Landing

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Abstract

The first section of the chapter contrasts a cognitive systems engineering (CSE) approach to task analysis with classical approaches. The critical difference is that a CSE approach is designed to provide a “survey” of the meaning landscape – what are the constraints that might guide adaptation. Classical approaches tend to focus the task analysis on “routes” or specific behavior trajectories (the one best way) within the domain. The second section provides a brief account of an on-going task analysis to understand the task of flying a precision instrument approach. This section provides samples of what we have learned from studying the history of aviation, reading authorities on flying, developing a synthetic task environment for landing, learning and teaching people to fly the simulation, observing and talking with experienced pilots, and talking with aeronautical engineers.

Introduction: Where are we coming from and where are we going?

The idea of “task analysis” can be traced to the early “time and motion” studies of the “scientific management” approach to work (Taylor, 1911; Gilbreth & Gilbreth, 1917). The general approach was first to describe a manual process in terms of fundamental elements (e.g., therbligs –
elements of motion). The second step was to improve upon the process by designing methods, tools, and jigs that eliminated wasted motions and that allowed less efficient motions to be replaced with more efficient motions. The focus was on activity and the goal was to use experimental methods to discover the “one best way.” Over the years the notion of “activity” has been expanded to include not only physical motions, but also cognitive operations (e.g., interpolates, verifies, remembers, calculates, plans, decides). However, the underlying theme has remained much the same – “the dissection of human work into ‘tasks,’ and the further analysis thereof” (McCormick, 1976, cited in Drury, Paramore, Van Cott, Grey, & Corlett, 1987).

Thus, work has been viewed as a sequence of activities or “tasks.” The job of work designers has been to discover the optimal sequence (the one best way); and to provide the instructions, tools, and incentives required so that operators would follow the optimal “route” through the work domain. As systems have become more complex, there has been a tendency to split the responsibilities for work design between the domain engineers and the human factors engineers. The domain engineers would focus on the work process and they would design the tools (the aircraft or nuclear power plant) and the operating procedures. That is, they would choose the routes that operators should take through the work domain based on an understanding of the process constraints and the safety requirements. These routes would then be communicated to the human engineers in terms of procedures and regulations. The job of the human engineers was to design the interfaces, warnings, instructions, training, and incentives necessary to guide the operators along the chosen routes (i.e., to get humans to follow the correct procedures).

Thus, a fundamental assumption of traditional task analysis has been the idea of “one best way.” This assumption tended to work well for domains that Perrow (1984) would describe as linear (“a system with a well-established technology, standardized raw materials, and linear production system,” p. 333). In these domains, the processes are well understood and predictable. Thus, it is possible to constrain behaviors to conform to predetermined routes formulated by the domain engineers. As Perrow (1984) observes:

When failures occur, as they inevitably will, they will not interact in unexpected and incomprehensible ways, but in expected and visible ways. The system programs responses for these infrequent but expected failures; the responses are determined at the top or in design, and employees at all levels
are expected to carry them out without question... . Repeated drills will insure fast and appropriate reactions, but the reactions are prescribed ahead of time, by the central authority (p. 333, emphasis added).

However, in domains that Perrow (1984) characterized as complex (e.g., nuclear power plants and universities) the possibility of multiple failures and unexpected interactions makes it impossible for a designer or centralized authority to prescribe solutions in advance. Perrow (1984) observes that in order to respond appropriately to disturbances in these complex systems:

Those at the point of the disturbance must be free to interpret the situation and take corrective action.... To do this they must be able to “move about,” and peek and poke into the system, try out parts, reflect on past curious events, ask questions and check with others. In doing this diagnostic work (“Is something amiss? What might happen next if it is?”), personnel must have the discretion to stop their ordinary work and to cross departmental lines and make changes that would normally need authorization (p. 332–333).

Another dimension that Perrow (1984) used to characterize systems was the nature of the coupling or dependence among components. He noted, that for complex and loosely coupled systems like universities where individuals have a high degree of independence, the peeking and poking around needed to discover solutions to unexpected faults (or unexpected opportunities) is typically not a problem. This is because the “loose coupling gives time, resources, and alternative paths to cope with the disturbance and limit its impact” (p. 332). However, society has been reluctant to allow “peeking and poking” around in complex, tightly coupled systems like nuclear power plants and air transportation systems with the potential for accidents of catastrophic impact. And, in fact, the interfaces to these systems, which have been designed to support procedures, do not facilitate exploration. The result is that we have typically tried to manage these complex systems using the “scientific management” philosophy in which a centralized authority prescribes the “one best way.” I (the senior author) can remember an instance very early in my career where I was invited to visit a nuclear power plant in the Southeastern United States to discuss the role of human factors. A manager argued that the solution to human factors problems was very simple: “The first time an operator makes an error, slap his hand. The second time he makes the error cut off his finger.” The result of this
attitude is that accidents remain a “normal” feature of these systems (to paraphrase from Perrow). The particular nuclear power plant that I was visiting has been notorious for its poor safety record.

The inadequacy of “procedures” for managing complex systems is graphically illustrated in Vicente’s (1999) anecdote about “malicious procedural compliance.” Control room operators found themselves caught in a double bind when they were being evaluated in a test simulator. When they deviated from standard procedures (in ways that they knew were necessary to meet the operational goals) they were given low scores for not following procedures. When they rebelled and followed the procedures exactly (even though they knew the procedures were inadequate) they crashed the simulator and were penalized for “malicious procedural compliance.”

The emergence of Cognitive Systems Engineering (Hollnagel & Woods, 1983; Rasmussen, 1986; Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999; Flach & Rasmussen, 2000) reflects a recognition that classical approaches to work design will not be effective in complex systems. In these systems the “procedural” aspects of work are typically automated. The human operator is included in the system to creatively deal with the unanticipated contingencies that were not (and probably could not have been) anticipated in the design of the automated systems (Reason, 1990). The human operators’ ability to diagnose faults and to adaptively respond so that these faults do not become catastrophic accidents is a critical resource for safe and effective systems. With cognitive systems engineering the work design problem shifts from:

how to constrain operators to follow predetermined routes through the work domain

to

how to provide operators with the survey knowledge of the work domain that they need to adaptively respond to unexpected events.

With cognitive systems engineering the focus of analysis shifts from “activities” or “procedures” to “situation awareness” or “meaning.” That is, the goal of work design is not to simplify or structure the operators’ behaviors, but to provide the operators with the information required for a deep understanding of the processes being controlled so that the operators can assemble the appropriate actions as required by the situations encountered. To do this, the cognitive engineer has to bridge between the domain engineers (who generally have knowledge about the deep structure of the processes being controlled; who know what is
meaningful) and the human engineers (who are responsible for the design of interfaces, instruction manuals, and training). The goal is to structure the interfaces, instructions, and training so that they reflect the “deep structure” (provide survey knowledge) of the work domain, as opposed to merely communicating procedures (route knowledge). For those not familiar with the distinction between survey and route knowledge -- route knowledge specifies the path from one location to another in terms of a specific set of actions (e.g., turn right at the first stop sign, then go five blocks, etc.). Survey knowledge specifies a more general knowledge about the relative layout of the environment (e.g., a map showing the relative locations of start and destination along with alternative paths between them). In essence the goal is to “loosen” the tight coupling (in Perrow’s sense) by enriching the information coupling between operator and process. In other words, instead of providing operators with specifications of a route, the goal is to provide a rich map of the work space. By enriching the information coupling between operator and the controlled process, it becomes more feasible for the operator to “peek and poke” into the process to discover solutions to unanticipated events before they result in catastrophic consequences.

The difference between survey knowledge (needed in order to discover new solutions) and route knowledge (sufficient for procedure following) can be very subtle, and this distinction has been difficult for many classically trained human factors engineers to appreciate. To them, the procedures are “what’s meaningful.” From their perspective, knowing where you are in a sequence and knowing what action comes next is all an operator should need to know. In fact, arguments have been made that it is best to restrict operators’ knowledge to the prescribed procedures to protect against undesirable variability from the human element in the system. But the challenge is this: how does an operator know what to do next when the path prescribed by the procedures is blocked? What does the operator need to know, when the standard procedures don’t meet the functional objectives for the process? In this situation, operators who only know procedures will be lost. The challenge of cognitive systems engineering is to consider what kinds of information would be useful for operators, so that they can go beyond the procedures when required (or alternatively when desirable due to some opportunity for improvement).

Operators with survey knowledge should be able to “see” the procedures in the context of the work domain constraints. Such operators should be able to see a procedure in relation to the other opportunities for action. They should be able to discriminate when the standard procedures
are the best way and when they are not! Thus, providing “survey knowledge” means making the work domain constraints “visible” to the operators through instructions, training, and interface design. And trusting that operators with this enriched view will choose the best paths. Rasmussen and Vicente (1989) have articulated this idea using the label “ecological interface design” (EID). The general theme of EID is to use the power of representations to reveal the deep structure of processes to the operators responsible for controlling those processes (see also Rasmussen, 1999; and Vicente, In press).

For the past four years we have been attempting to apply the EID approach to the development of alternative displays for the “glass” cockpit. The remainder of this paper will focus on the cognitive task analysis process that has informed our display development. We will not describe the graphical displays here. Descriptions of the display are available in other sources (Flach, 1999; Flach, 2000; Jacques, Flach, Patrick, Green & Langenderfer, 2001). In this paper, we will try to provide a few snapshots of our efforts to discover the “deep structure” associated with flight control and will share what we have learned about flying (particularly the precision approach). The hope is that our search might serve as a “case study” to illustrate a work analysis process designed to discover what is meaningful.

A Search for Meaning

The aviation domain is interesting from the perspective of Perrow’s (1984) framework, in that air traffic control is classified as a linear system, but piloting is classified as a complex system. Thus, for air traffic control safety is currently managed through a centralized authority and the paths through the sky are tightly constrained by procedures and regulations prescribed by this centralized authority. This management style is successful because there has been plenty of buffer room within the air space to effectively linearize the air traffic control problem. However, with increasing air traffic density the probability for unexpected interactions is increasing (the system is becoming more complex), leading to a demand for a more distributed management style, where pilots will have greater discretion and authority (i.e., free flight) (Billings, 1995; Rochlin, 1997; Woods & Sarter, 2000).

For the task of piloting, unexpected disturbances and interactions are normal. Although it is possible to automate flight from take-off to landing, it is impossible to reduce piloting to a fixed set of actions or
procedures. That is, in piloting (as with any control task) there is no single set of actions that will produce the same desired output in every context. In other words, the actions (e.g., control manipulations) must be tuned to the particulars of each situation (no take-off or landing will ever be identical to another). In fact, this is the essence of a control (closed-loop) problem as Powers (1998) noted:

The interesting thing about controlling something is that you can't plan the actions needed for control before hand.... if actions were not variable, if they did not vary exactly as they do vary, in detail, the same consequences couldn't possibly repeat. The reason is that the world itself shows a lot of variation, and for every variation, our actions have to vary in the opposite way if any particular consequence of acting is to occur again and again. Controlling means producing repeatable consequences by variable actions (p. 3 – 5).

Although piloting involves much procedure following and although automated systems are increasingly capable of closing inner control-loops, this does not mean that the human is no longer part of the control system. In fact, just the opposite is true. Humans remain in complex systems to respond to disturbances that could not be anticipated in the design of automated systems and to tune the procedures to the inevitable situational variability (Reason, 1990). That is, the operators’ role is to adaptively respond to unexpected events. Thus, interface design has to take a “control theoretic perspective” to try to define the information requirements of the control problems that a human supervisor may be asked to solve (Rasmussen, Pejtersen, & Goodstein, 1994, p. 8). This requires that the operators have information about the “state” of the process; about the dynamic constraints that govern the transformations from one state to another; and about the associated costs and benefits relative to the functional goals for the system.

Classical single-sensor-single-indicator interfaces (e.g., the “steam gauge” cockpit) generally were designed to represent most of the “state variables.” However, there appears to have been little consideration to the dynamical constraints among these variables or to the relation of these variables to functional goals of the system. The result is plenty of data, but little help for the processes of information or meaning extraction (Flach, 1999). For example, airspeed would be an example of a critical state variable for flight – the airspeed indicator was one of the first instruments introduced to the cockpit. Airspeed data is displayed and “speed bugs” (see Hutchins, 1995a) can be used to identify goal speeds

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and to a certain extent the acceptable margins of error. However, the
dynamic relations between airspeed and other states of the aircraft are not
represented in the interface. So, while deviations from the desired
airspeed are well represented – solutions (the ways to recover a target-airspeed) are not well specified.

What should a pilot do when airspeed is lower or higher than the
target speed? That is, what actions should the pilot take so that the
aircraft will speed-up or slow down to the target speed? Is there anything
in the form of the representations used in standard cockpits that helps a
pilot to “see” what to do? Of course, experienced pilots generally
“know” what to do – but is this because of the interface design or in spite
of this design? An important question, for a cognitive task analysis is
what do experienced pilots know (either explicitly or implicitly)? Or
better still, what should experienced pilots know? The challenge of EID
is – can this knowledge be externalized as part of the interface, so that
less experienced pilots will be able to see what more experienced pilots
know? Or so that any pilot can see what they need to know in order to
keep the system within the field of safe travel.

**An Historical Perspective**

A survey of the cognitive task analysis literature shows that much of
the recent focus has been on knowledge elicitation (Cooke, 1992) and
naturalistic observation (Klein, Orasanu, Calderwood, & Zsambok,
1993). There is currently a stampede of human factors engineers rushing
into the field to talk with and watch experts in their natural habitat. While
we agree that this is an essential component of any search for meaning, it
is important to complement fieldwork with less glamorous library
research, that is, *table-top analysis*. We are tempted to say that a
thorough table-top analysis is a prerequisite to effective fieldwork, but
recognizing the iterative and opportunistic nature of discovery, we make
the more modest claim that early investments in table-top analysis can
greatly facilitate later interactions with experts in the field.

Classically, table-top analysis has focused on instructions, procedure
manuals, and training manuals in order to identify the desirable flow of
activities. However, in searching for meaning it is generally necessary to
dig deeper to discover the rationale that guided the choice of procedures.
We have found that a good place to begin this search for meaning is to
study the historical development of the work domain. This is particularly
well illustrated by Hutchins’ (1995b) analysis of the domain of ship
navigation. This analysis included a study of the historical evolution of navigation in western culture, as well as comparisons with navigation in other cultures. This type of analysis helps to make the meaning and assumptions behind the current tools and procedures explicit. In biology, it is noted that “ontogeny recapitulates phylogeny.” It is tempting to hope that the evolution of a work domain (phylogeny) may provide insights to the ontogenesis of expertise within that domain. This hope has been well substantiated in our study of the evolution of the flight domain.

Let’s begin by considering the early development of flight. Anderson (1978) writes:

During most of the nineteenth century, powered flight was looked upon in a brute-force manner: build an engine strong enough to drive an airplane, slap it on an airframe strong enough to withstand the forces and generate the lift, and presumably you could get into the air. What would happen after you get in the air would be just a simple matter of steering the airplane around the sky like a carriage or automobile on the ground – at least this was the general feeling. Gibbs-Smith calls the people taking this approach the “chauffeurs.” In contrast are the “airmen” – Lilienthal was the first – who recognized the need to get up in the air, fly around in gliders, and obtain the “feel” of an airplane before an engine is used in powered flight. The chauffeurs were mainly interested in thrust and lift, whereas the airmen were firstly concerned with flight control in the air. The airmen’s philosophy ultimately led to successful powered flight; the chauffeurs were singularly unsuccessful. (p. 17–18)

The chauffeur’s philosophy and its futility were illustrated by Langley’s failed attempts at powered flight in 1903. Twice he attempted to catapult his assistant Manly into the air. However, as Anderson notes he “made no experiments with gliders with passengers to get the feel of the air. He ignored completely the important aspects of flight control. He attempted to launch Manly into the air on a powered machine without Manly having one second of flight experience” (p. 22). It is quite lucky that Manly was not seriously injured in either of the failed launches. Nine days after Langley’s second failed attempt, on December 17, 1903 the Wright brothers made their first successful flight at Kitty Hawk.

Biographers of the Wright brothers contrast their approach to the problem of flight with that of others who had failed. For example, Freedman (1991) wrote:
The Wrights were surprised that the problem of balance and control had received so little attention. Lilienthal had attempted to balance his gliders by resorting to acrobatic body movements, swinging his torso and thrashing his legs. Langley’s model aerodromes were capable of simple straight-line flights but could not be steered or maneuvered. His goal was to get a man into the air first and work out a control system later.

Wilbur and Orville had other ideas. It seemed to them that an effective means of controlling an aircraft was the key to successful flight. What was needed was a control system that an airborne pilot could operate, a system that would keep a flying machine balanced and on course as it climbed and descended, or as it turned and circled in the air. Like bicycling, flying required balance in motion. (p. 29)

In contrasting the approaches of Lilienthal and Langley with the approach of the Wrights it is obvious that the Wrights’ approach was more consistent with what today would be called a “human-centered” approach to design. Lilienthal and Langley designed wings to be passively stable and they left it up to the pilot to solve the problems of balance and control that were left over. Langley tended to be more of a “chauffeur,” focusing on the propulsion problem and ignoring the control problem altogether. Lilienthal was more of an “airman”, but his designs provided little support to help the human manage the control problem. “In all Lilienthal machines, the pilot hung upright between the wings, controlling the craft by shifting his own weight to alter the center of gravity” (Crouch, 1989, p. 143). The fact that Lilienthal was able to make “controlled” flights in his “hang gliders” was a testament to his athletic skill. However, it is extremely risky to engineer a system around the skills of exceptional humans.

The Wrights engineered the system around the control problem. They focused their efforts on designing “a control system that an airborne pilot could operate.” They succeeded because they engineered a system that allowed manipulation of the flight surfaces. Perhaps the most significant contribution was the invention of “wing-warping” to aid in balance and control. Freedman (1991) noted that the insight for wing-warping began with observations of “buzzards gliding and soaring in the skies over Dayton, they noticed that the birds kept adjusting the positions of their outstretched wings. First one wing was high, then the other” (p. 29). Freedman (1991) continues:
It occurred to the brothers that a bird can balance itself and control its flight by changing the angle at which each wing meets the oncoming air. When the bird wants to begin a turn, for example, it tilts the leading edge of one wing up to generate more lift, making that wing rise. At the same time, it tilts the leading edge of the opposite wing down, causing that wing to drop. Its body revolves toward the lowered wing. When it has revolved as far as it wishes, it reverses the process and begins to roll the other way. (p. 29)

Wing-warping involves twisting the semi-rigid wing so that when one end of the wing was up the other was down. Wilbur Wright reportedly got the idea for wing-warping while holding a cardboard box that had contained an inner tube. He noticed that by twisting the ends of the box in opposite directions he could accomplish the control function that had been observed in the buzzards. The first practical aircraft, the Wright Flyer III, had three controls. One hand controlled an elevator. The other hand controlled a rudder. Finally, a saddle device at the pilot’s hip allowed him to warp the wings by shifting his hips. As Freedman (1991) notes, the Wright’s solution to the control problem remains the foundation for modern flight.

Except for the engine, their 1902 glider flew just as a Boeing 747 airliner or a jet fighter flies. A modern plane “warps” its wings in order to turn or level off by moving the ailerons on the rear edges of the wings. It makes smooth banking turns with the aid of a movable vertical rudder. And it noses up or down by means of an elevator (usually located at the rear of the plane). (p. 64)

These Wright brothers discovered the first workable solution to the “manipulation” aspect of the inner loop control problem. However, pioneers in aviation soon realized that the control problem involved perception as well as manipulation. It soon became clear that the unaided human senses did not provide all the information necessary for stable control. Edwards (1988) reports:

Experience indicated ... that certain basic aids were essential in order to achieve an acceptable level of control. Early amongst these was the famous piece of string tied either to the trailing edge of an elevator or to a lateral frame member so that the pilot could avoid skid or slip during a turn by keeping the fluttering string parallel to the fore-and aft axis of the aircraft. Without
this aid, turns could easily lead to a spin from which there might be no recovery. (p. 6)

Gradually, other instruments were introduced to supplement the information that was directly available to the human senses. These included airspeed indicators to reduce stalling accidents, compasses, and barometric altimeters. However, for the most part, early aviators “tended to relegate instruments to a subsidiary role, and little or no mention was made of their use in the programs of flight training” (Edwards, 1988, p. 6). This is reflected in this historical note from Ocker and Crane’s (1932) book on the theory of “blind flight:”

The equipment of the airplane prior to 1914 was characterized by an almost complete lack of instruments, both engine instruments and flight instruments. This was due, no doubt, to a number of causes, principal among these being that there always has been a studied dislike of instruments by the pilot. The pilot likes to feel that he is an artist at flight control, and in plying his art feels that his natural instincts are a better guide to the performance of his craft than any number of instruments. The natural result of this psychology was an airplane with few instruments (p. 9)

It is interesting to note that there was great initial skepticism about early instruments. This skepticism about instruments was illustrated by Ocker and Crane’s (1932) description of a situation where pilots’ from one “airway” company returned several turn instruments because they were defective. The instruments appeared to give correct readings in clear weather, but did not seem to work in clouds. The instruments were tested and shown to work correctly. The problem, as we now know, was that the pilots were putting their faith in unreliable vestibular feedback, rather than in the reliable instruments (e.g., Leibowitz, 1988). Thus, a significant aspect of instrument training is to help pilots to transfer their trust from the unreliable “seat of the pants feelings” to the reliable instruments.

We could continue this story, but we hope that this brief review of some of the issues of early flight illustrates the value of taking an historical perspective. The “chauffeur’s” approach to flight is often replicated in novice pilots who attempt to generalize their experiences controlling ground and sea vehicles to the task of flying. This is reflected in both their intuitions about control and their choice of a coordinate system for spatial orientation. Novices tend to orient to their intrinsic coordinate system (e.g., upright as signaled by their eyes under visual
conditions and their vestibular system in instrument conditions) and for some it takes extensive training to get them to trust the world (i.e., horizon) centered coordinate system presented by their instruments. A goal for CSE and EID is to facilitate the transformation from “chauffeur” to “aviator.”

One Pilots’ Opinion

Another significant stimulus to our early thinking about the flying problem was Langewiesche’s book “Stick and Rudder: An explanation of the art of flying.” This book which was originally published in 1944 is still valued by some general aviation flight instructors today. Langewiesche’s book was originally brought to our attention due to his insights about the visual information used in an approach to landing, which was an important inspiration for Gibson’s (1966) conception of the optical flow field. Thus, his insights have not only influenced pilots, but they have inspired an important area of scientific research associated with visual control of locomotion.

The following quote describes Langewiesche’s goals for his book. These goals resonate with the motives behind CSE and EID.

It may be that, if we could only understand the wing clearly enough, see its working vividly enough, it would no longer seem to behave contrary to common sense; we should then expect it to behave as it does behave. We could then simply follow our impulses and “instincts.” Flying is done largely with one’s imagination! If one’s images of the airplane are correct, one’s behavior in the airplane will quite naturally and effortlessly also be correct. (p. 4).

For Langewiesche, the key to understanding a wing was the Angle of Attack (AOA - []). He labeled the Angle of Attack as the “single most important fact in the art of piloting” (p. 5). The AOA is the angle at which a wing’s chord line meets the relative wind. Typically, the relative wind will be parallel and in the opposite direction to the motion of the aircraft. AOA is related to, but not the same as the pitch angle or the glide path angle of the aircraft. Figure 1 illustrates the relations among these three angles. Aircraft are generally designed to stabilize around a specific AOA dependent on the current configuration (e.g., trim). Thus, AOA is a key to understanding how the aircraft naturally behaves so that the pilot can work with the aircraft, rather than against it. Also, Langewiesche felt that AOA was critical for developing intuitions about
the function of the various controls. Figure 1 clearly illustrates that even with longitudinal control an airplane does not typically move in the direction it is pointed as with most land vehicles. The AOA is an important factor relating the orientation (pitch - \( \theta \)) and the path angle (direction of motion - \( \delta \)) of the aircraft. Thus, for Langewiesche, an understanding of AOA can help a pilot to see how the throttle can function as an “altitude” control and the elevator as an “airspeed” control.

One of the difficulties in grasping the AOA, as Langewiesche observed, is that it is invisible to pilots. That is, since the pilot can’t see the “wind,” the AOA can’t be seen without instruments. While it can be measured, most aircraft did not have an instrument to measure or to display AOA. Since AOA is an attribute of motion, static diagrams can also be misunderstood. This misunderstanding is frequently because the motion of the wing (and/or) direction of relative air are typically depicted as abstract vectors and are less salient than the orientation of the wing within the diagram.

Langewiesche saw an understanding of AOA as the foundation for piloting skill and the failure to understand AOA as a contributing factor in aviation accidents—“the stall is the direct and invariable result of trying to fly at too large an Angle of Attack” (p. 20). A stall refers to the situation where a wing no longer functions to support the aircraft. A wing will produce more lift at larger AOA up to a limit. Beyond this limit the wing will cease functioning. At this point there will be insufficient lift for controlled flight and the aircraft begins to fall out of the air. In Langewiesche’s day, stall was a cause of many accidents. Wilson (1979) reported that “two-thirds of all (general aviation) fatal accidents in the 1934 – 38 period involved stalls, spins, or both; in 1939 – 40, over half the fatal accidents originated in the pilots’ inability to recognize or recover from stall” (p. 36). However, since Langewiesche’s day recovering from a stall has become easier due to improvements in the design of some aircraft and stall warning systems have been introduced to help alert pilots to the problem when it occurs. For example, by 1946 (two years after Langewiesche’s book), the Civil Aeronautics Authority’s (CAA’s) Technical Development and Evaluation Center had developed three different stall-warning models, each reacting to changes in air flow over the wing by activating a horn or flashing light in the cockpit. In 1951, the CAA sent a specially equipped plane around the country to demonstrate stall recovery techniques. These steps dramatically reduced the number of stall-spin accidents for the last quarter of 1951, from 113
to 39 accidents. Although the alarms and improved handling qualities have made aviation safer, they have not necessarily made pilots smarter. That is, they do not help pilots to understand the development of conditions that lead to stall. From a CSE perspective, the challenge is how can we help pilots to understand and anticipate the conditions of a stall, so that the warnings rarely are needed?

From the perspective of CSE and EID, AOA attracted our interest. It seemed clear that AOA was Langewiesche’s answer to the question of “what should a skilled pilot know?” Thus, we began with an initial hypothesis that it might be an important element of the “deep structure” of flight control that is not well represented in most cockpits. Early in our analysis we began to wonder if making AOA explicit could not only help prevent stalls, but also enhance general piloting abilities?

**Participant Observations in a Synthetic Task Environment**

In this phase of our search for meaning, we made observations in a flight simulation that we developed. Key to this phase was our experiences of making the simulation work to the satisfaction of the pilots (so that they could fly precision approaches consistently using their normal experiences, without additional training in the simulation). Also, the process whereby one of the experienced pilots in our group trained two of the other authors, who were not pilots, was important to our understanding of the precision approach problem.

For those in the group who were naïve participant observers trying to learn the precision approach task in the simulator, the most striking problem was what we perceived as a cross-coupling across the controls. While we struggled to align the course of the aircraft with the runway we would lose track of our glide slope (and suddenly the ground would be looming on the screen or the runway would be passing far below us). If we focused on our glide slope, we would soon find our course helplessly out of alignment. Attention to one aspect of the approach invariable resulted in unintended deviations with respect to another dimension of the task.
Figure 1. Three situations where the aircraft is pointing in the same direction relative to the horizon (pitch), but is moving in three different directions (three different flight paths -- cruise, climb, and descent) none of which correspond to the direction it is pointing. The differences between pitch and flight path are caused by different air speeds resulting in three different AOAs.

It was interesting to us that this coupling problem does not get much discussion in the literature on aviation psychology. In a chapter on pilot control, Baron (1988) described the degrees of freedom for flight:

The aircraft moves in three-dimensional space and has, from the standpoint of its basic, dynamic response, six degrees of freedom; it can translate linearly in three ways (forward-backward, left-right, up-down) and it can rotate angularly about three separate axes. The motions of the airplane are actually determined by the
action of a variety of aerodynamic, gravitational, and thrust forces and moments, some of which can be controlled by the pilot using the control manipulators. For conventional, fixed-wing aircraft, there are four controls (elevator, aileron, rudder, throttle). With these, and changes in configuration, the pilot can introduce control moments about three axes (pitch, roll, and yaw) and control forces along the aircraft’s forward-aft body axis (through thrust-drag modulation). Clearly for complete control of all six degrees of freedom, there must be interaction or coupling among motions. The most familiar example of this are motions in which the pilot rotates the aircraft to orient its lift force so as to produce appropriate sideways and normal accelerations (e.g., bank-to-turn) (p. 349–350).

After introducing the degrees of freedom problem, Baron quickly dismissed it noting that “although there is some inevitable coupling among all six degrees of motion of the aircraft, some interactions are quite strong while others may be virtually negligible” (p. 350). From this point, Baron’s discussion of control tended to focus on the longitudinal (glide path) and lateral (course) control dimensions as essentially independent control tasks. A similar approach is seen in Roscoe (1980). In terms of the aerodynamics, the interactions between lateral and longitudinal control axes should generally be small, especially when the bank angles are small as would be expected for precision approaches. Our experiences learning to fly the precision approach, however, were not consistent with this analysis. The interactions between control dimensions seemed to be a significant factor relative to the difficulty of flying a precision approach. This suggests that the major source of the interactions was our ineffective control strategy. The interactions we experienced most likely reflected poor time sharing – error was building-up due to inattention to one axis, while focusing on the other.

Figure 2 was our early attempt to illustrate the interactions among the control dimensions. The boxes are empty because our goal was not to specify precise quantitative relations, but simply to visualize the couplings among the variables. There are two significant features of this diagram relative to other representations in the aviation psychology literature (i.e., Baron, 1988; Roscoe, 1980). First, Figure 2 makes the interactions across flight dimensions explicit, whereas others illustrate the longitudinal and lateral control tasks independently. Second, the diagram is structured so that the outputs reflect the dimensions that would typically be used to “score” an approach as safe or unsafe. In other
illustrations of the control tasks the “outputs” are typically altitude and lateral displacement (other dimensions are included as internal state variables). Note that there are six output variables, these six variables span the control space (six degrees of freedom). However, note that the dimensions of the “control space” are different from the dimensions that are sometimes used to characterize aircraft state (i.e., three positions (x, y, & z) and three rotations (pitch, roll, and, yaw). The rotational dimensions are the same, but the x (e.g., distance to runway) and z (altitude) dimensions of standard representations are replace by airspeed and glide slope in Figure 2. Also, the glide slope and course (y) variables are referenced to the touchdown target on the runway, not the aircraft. This change reflects the goals for a precision approach. Also, note the central position of AOA within the diagram, consistent with Langewiesche’s emphasis on this factor. Finally, the coupling between the lateral and longitudinal control axes is “dashed” to reflect the fact that the magnitude of these interactions may depend heavily on the skill of the pilot.

Figure 2. A schematic representation of the piloting problem designed to emphasize the couplings between control axes and the performance indices that would be used to evaluate the success of an approach-to-landing.
As we thought more about the degrees of freedom problem, we began to think about priorities among the different dimensions of a precision approach. Figure 3 shows our attempt to illustrate these priorities in a hierarchical means-ends graph. Again, this diagram shows the cross couplings across the input or control dimensions and the central role of AOA in mediating those interactions.

![Hierarchical Means-Ends Graph](image)

**Figure 3.** A hierarchical representation designed to emphasize means-ends relations associated with an approach-to-landing.

The frustrations in learning the landing task helped us to appreciate the difficulties of the flight control problem. There were clearly strong temptations to “chauffeur” the aircraft to the runway based on our experiences with land vehicles. And the adjustments needed in order to adapt to become “aviators” were not readily apparent. This had all the characteristics of a “workload” problem. However, the “load” was not due to “too much data” or to a processing limit. Rather, it was due to poor attunement to problem structure (a meaning processing problem). It
was difficult for us to take advantage of the natural constraints to “parse” the many dimensions of the control problem into a manageable number of meaningful “chunks.”

**Process Tracing in Synthetic Task Environments**

When an experienced pilot flies an airplane, when he puts it through climbs and glides, turns, stalls and spins, take-offs and landings, he is asking himself all the time, “Where, at this moment, is the air coming from? And at what angle are my wings meeting it?” Most pilots would of course deny that they ever think such a thing. And it is a fact that many excellent pilots don’t even know the meaning of the words Angle of Attack and Relative Wind (Langewiesche, 1944, p. 23 – 14.).

Our interactions with pilots confirmed the above observations of Langewiesche. Many pilots did not explicitly understand AOA and most of them saw little value to a display of AOA in the cockpit. Was this a sign that we were on the right track or the wrong track?

Rather than AOA, the variable that seemed to be of most concern for our experienced pilots was airspeed. Note that AOA and airspeed are tightly coupled in flight. The first thing that most experienced pilots wanted to know before attempting to land the simulation was the “final approach speed.” Further, tracking the final approach speed (i.e., correcting deviations from the target speed) was a top priority. Also, surprising to those of us who were still thinking like chauffeurs, the primary control action for correcting deviations from the target airspeed was fore-aft deflections of the stick, not the throttle. Pilots tended to use a “pitch-to-speed” mode of control for the large aircraft that our simulation was based on as illustrated in the top half of Figure 4. However, we have been told that there are situations where alternative modes of control are more common (e.g., carrier landings). Also, the automated systems in some aircraft use a mode of control more similar to the “pitch-to-path” mode illustrated in the bottom half of Figure 4. As Holder and Hutchins (2001) describe, this can sometimes result in an “automation surprise” for pilots:

Speed can be controlled by thrust while thrust is at idle only if the vertical path has been constructed such that idle thrust is the amount of thrust required to produce the target speeds. This computation cannot be done by any human pilot. But, it is exactly what a managed descent in an Airbus or a VNAV path
descent in a Boeing does. Many pilots see this as magic because they literally cannot imagine how it is done (p. 3).

Figure 4. Two modes of controlling speed. The top panel shows the pitch-to-speed mode used most commonly by pilots. In this mode the throttle is typically set at a fixed level and speed is regulated using primarily the elevator (pitch). The bottom panel shows the pitch-to-path mode used in some automatic landing systems. In this mode the path is regulated using the elevator and the speed is tracked with continuous modulations of thrust.

Figure 5 attempts to illustrate what we learned from talking with the experienced pilots and from watching them land the simulation. The pilots tended to lock out degrees of freedom to simplify the control problem. First, the pilots set the throttle so that the aircraft will operate in the “ballpark” of the target approach speed (about 75% of full throttle for the aircraft and configuration used in our simulation). Then the pilot used fore-aft deflections of the stick to track the target airspeed and the glide slope. With the throttle fixed at the appropriate point the airspeed and glide slope will be functionally coupled. That is, higher than target speed typically indicates that the approach is steeper than desired and lower than target speeds typically indicates that the approach is shallower than
desired. The pilots tended to use right and left deflections of the stick synergistically with the fore-aft stick (elevator) to control course deviations. For many of the pilots the rudder became the primary control for correcting small deviations in the region of final touchdown. For small corrections, rudder controls gives yaw angle and slip angle, and thereby course changes. This is faster than aileron control, which needs an extra integration (from roll, to bank angle, and then to course change) and it tends to minimize unintended disturbances to other control targets (glide path and roll attitude).

![Diagram](image_url)

**Figure 5.** A hierarchical representation that illustrates constraints that skilled pilots introduce to help manage the degree of freedom problem. Dotted lines indicate paths that are constrained and dark solid lines indicate primary functional control paths.

Thus, consistent with the decompositions of the control task described by Baron (1988) and Roscoe (1980), pilots tended to manage the control problem so that interactions between the glide slope (longitudinal axis) and the course (lateral axis) were minimized. This probably reflects a more effective distribution of attention between the two axes. In this sense, skill development involves discovering a “smart”
way to “chunk” the control problem to utilize natural constraints and minimize the dimensionality of the control problem (e.g., Runeson, 1977).

Several factors contribute to accomplishing an appropriate decomposition of the control task. First, the coupling is not symmetric. Course control using ailerons is more likely to impact the glide slope, than vice versa. Course control generally requires coordinated motion of the stick right-left and fore-aft (sometimes with rudder control) – whereas, glide slope corrections can be accomplished using only the fore-aft dimension of the stick. Although the interactions are small, course corrections will typically impact airspeed and glide slope, however, corrections to glide slope can be accomplished with no change to course.

A second factor effecting the decomposition of the control task is that the spill over between axes is highly dependent on the ability to control the individual dimensions. Correcting a course deviation error requires a more complex control-input than correcting a deviation from glide slope. Remember that discovering the solution to “turning” the aircraft was a major obstacle to the design of the first aircraft. Course control is a fourth-order problem – there are four integrations between the control manipulation and the control variable. Glide slope control is only third-order. A fourth-order control problem is extremely difficult (essentially impossible) for a single-axis tracking-task where the output is the only feedback. To manage this control task the pilot must be able to anticipate (predict) the effects of his control actions, before they show up as changes in the final control variable. From our observations of pilots and our experiences learning to fly the simulation we discovered that attending to the heading indicator (heading and rates of change of heading) can be helpful for anticipating effects of actions to correct course deviations. The heading indicator, rather than the course deviation needle of the flight director, tended to be the primary reference for course control. By referencing intermediate states (roll and heading) the pilot can effectively reduce the fourth-order problem to multiple nested, lower-order control problems (See Baron, 1988; Figure 11.4, p. 355).

It is our understanding that some flight director displays actually combine heading and change of heading (or some other index of the derivative and second derivative or course deviations) to drive the horizontal needle of the flight director. In the language of manual control the course deviation indicator is “quickened” to reduce the effective order of control from fourth- to first-order. However, when we inquired
with manufacturers of these instruments, we were surprised to learn that the algorithms driving the flight director are “proprietary.” We were also surprised that pilots show little concern or curiosity about the internal “logic” of these displays. This doesn’t necessarily indicate a blind trust on the part of the pilots, but rather a confidence that has evolved based on an ability to validate the flight director against other redundant sources of information (including the optical flow field and other instruments).

Our observations and discussions with pilots indicated that, for many pilots, correcting course deviations tended to be more difficult. We found from our own experience learning the task that as our skill at controlling course deviations improved, the interactions across the control dimensions were much easier to manage. This does not necessarily indicate that one type of error is more or less important than another. Rather, the point is simply that the overall control problem tends to be easier, if the course errors are managed well.

As a result of our observations in the synthetic task environment our picture of the deep structure of the precision approach task changed. We began to see AOA not as a separate critical variable. Rather, we began to think of it as the nexus of the degree of freedom problem. We began to believe that adding AOA to the interface would not help to solve the meaning-processing problem. What novices needed was a better organization or configuration (i.e., chunking) of information so that the interactions among the control axes (largely mediated by AOA) were more apparent. It seemed to us that the problem was not lack of critical information, but poor organization of the information. We needed to think about better ways to “configure” the interface (Bennett & Flach, 1995) so that the meaningful interactions among the components of the task were better specified.

**Back to First Principles**

The effort to understand how an airplane flies is sometimes called “The Theory of Flight.” Under that name, it has a bad reputation with pilots. Most pilots think that theory is useless, that practice is what does it.... What is wrong with “Theory of Flight,” from the pilot’s point of view is not that it is theory. What’s wrong is that it is the theory of the wrong thing – it usually becomes a theory of building the airplane rather than of flying it. It goes deeply – much too deeply for a pilot’s needs –
into problems of aerodynamics; it even gives the pilot a formula by which to calculate his lift! But it neglects those phases of flight that interest the pilot most. It often fails to show the pilot the most important fact in the art of piloting – the Angle of Attack, and how it changes in flight. And it usually fails to give him a clear understanding of the various flight conditions in which an airplane can proceed, from fast flight to mush and stall. (Langewiesche, 1944, p. 4–5).

The search for meaning is often complicated by the fact that each of the disciplines associated with a domain (pilots versus aeronautical engineers) has their own perspective (flying versus building aircraft) and their own specialized jargon reflecting that perspective. These differences were striking, as we began to explore our understanding of the landing task and our display concepts with aeronautical engineers. This is reflected in our earlier discussion of the dimensions of the problem space – pilots and engineers tend to use different coordinates to index the same space. Figure 6 illustrates what we believe is an important difference in how aeronautical engineers and pilots approach the problem of flight. Aeronautical engineers tend to think about the “step-response” of an aircraft. That is, if a step-input is presented through one of the controls, what will the aircraft do? In evaluating this question, they have found it valuable to distinguish between the “short-period” and “long-period” response. Thus, when we asked aeronautical engineers what factors would determine whether “pitch-to-speed” or “throttle-to-speed” strategies would be more effective approach strategies – their first response was that it depended whether we were interested in the “short-“ or “long-period” response. At this point, communication was difficult. Pilots never talked about “short-“ or “long-period” responses. Even after the engineers explained the differences it wasn’t obvious to us which we should be more interested in. Although we are coming to believe that the short period response is most critical to the pilot’s control problem. Baron (1988) has a nice discussion that relates this decomposition to inner (short period) and outer-loop (long period) aspects of the control task. One way to think about the difference between short and long period responses is that the short period response is the instantaneous reaction of the aircraft to a command-input. The long period response is the aircraft’s natural motion before the aircraft settles into a steady state as its natural stability properties come into play (e.g., damping out the initial control effects). Note that in Figure 2 the links emphasize the short period interactions. To represent the long period effects, feedback loops
would need to be included to illustrate the natural stability properties of
the aircraft.

In contrast to aeronautical engineers, pilots tend to think about how
to produce “step-outputs.” That is, they want to know what control input
will move an aircraft from one state (where they are) to another (where
they want to be). It is important to note that both groups are asking
questions about the aircraft dynamics and both perspectives are
legitimate ways to ask about the dynamics. However, the translation from
one perspective to the other is not trivial and failure to make this
translation can lead to great difficulties in communication between
aeronautical engineers and pilots (not to mention the difficulty of
communicating with the psychologists).

![Diagram](image)

**Figure 6.** Two perspectives on the flying problem. Engineers choose a
framework that makes the “causal” relations associated with opposing forces
most clear. Pilots choose a framework that makes the "intentional" relations
associated with safe accomplishment of operational objectives most clear.

We found that aeronautical engineers also found it valuable to
decompose the control task along the longitudinal (they called symmetric
flight) and lateral (asymmetric flight) axes. Some further decomposed the
control problem into concepts of energy. For symmetric flight, total
energy (TE) could be decomposed into kinetic (KE) and potential energy
(PE). Kinetic energy is a function of the speed of the aircraft
(1/2*mass*velocity²) and potential energy is a function of the altitude
(mass * gravitational acceleration * altitude). In this context, the throttle
could be thought of as controlling the total energy, and the fore-aft stick
(elevator) could be thought of as governing the distribution of energy between (KE ≈ airspeed) and (PE ≈ altitude).

This provides an alternative way for thinking about the pilots’ approach strategy. The effect of fixing the throttle is to create a situation where energy out (due to drag) is greater than energy in. The throttle setting should be set so that the rate of energy loss (drag – thrust) is at a small constant value – that corresponds to the ideal glide slope for a given aircraft. The stick then is used to make sure that the energy loss is in terms of PE (altitude), rather than KE – by making sure that airspeed remains roughly constant. Table 1 shows how deviations from glide slope and airspeed map into the energy distribution and the implications for the appropriate response. Note that just prior to touchdown (PE near zero) a flare maneuver is executed to minimize vertical velocity at touchdown. This further reduces total energy at the point of contact with the earth – the residual KE is then dissipated after the aircraft is on the runway.

### Table 1: Symmetric Flight: Energy Management

<table>
<thead>
<tr>
<th>Airspeed Altitude</th>
<th>Too Slow</th>
<th>Too Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Too High</td>
<td>Energy distribution problem, push stick (elevator) forward to trade excess PE for needed KE.</td>
<td>Too much energy – throttle back.</td>
</tr>
<tr>
<td>Too Low</td>
<td>Too little energy – throttle forward.</td>
<td>Energy distribution problem, pull stick (elevator) back to trade excess KE for needed PE.</td>
</tr>
</tbody>
</table>

At this point we are beginning to wonder whether it might be useful to use the concept of energy and its partitioning (balance) between kinetic and potential energy as an organizational constraint in a graphical configural display. Energy is beginning to replace AOA as the lynch pin in our conceptual image of the flying problem. We are in the early stages of our discussions with aeronautical engineers. After some false starts, we are getting past the language differences so that we can think about the pilots’ control problems relative to dimensions that are meaningful to the aeronautical engineers. At this point, we are shifting focus from AOA to energy concepts as a way of thinking about how to parse the control problem and how to organize a graphical representation into meaningful
chunks. Our current belief is not that we need to “add” energy displays. Rather, the thought is that understanding the “energy balances” may be fundamental to developing configural representations that will organize the data into patterns that better reflect meaningful constraints on the control problem.

Figure 7. The abstraction/decomposition space is used to illustrate several different perspectives on the precision approach problem. (θ = flight path angle: V(dot)/g = longitudinal acceleration).

Figure 7 shows our current evolving image of the precision approach problem using the top three levels of Rasmussen’s (1986; Rasmussen et al., 1994; Also, see Bisantz & Vicente, 1994) abstraction hierarchy. Note that this is an “evolving” image – that is we are not satisfied that we have captured all the meaningful constraints. At the Functional Purpose Level, the goal of a safe flight is reduced to following a precision path as is typically specified by an Instrument Landing System (ILS) beacon. From the pilot’s perspective, this typically involves tracking the target landing speed and the ILS needles that provide glide path and course errors.

At the Abstract Function Level, the precision approach can be described as an energy management problem. Flying the approach can be described in terms of a constant decrease in potential energy, while
maintaining a fixed level of kinetic energy. This energy management problem can be decomposed to reflect some of the state variables \( g = \text{flight path angle; } V(\text{dot})/g = \text{longitudinal acceleration} \) and controls (throttle and elevator). The Abstract Function Level reflects the aeronautical engineer’s perspective on the precision approach problem.

The pilot’s perspective on the control problem can be seen at the Generalized Function Level of description. Here the control problem is described in terms of the targets (speed, glide slope, and course), important intermediate state variables, and the control surfaces. These top levels of the abstraction hierarchy should be fairly independent of the type of aircraft or landing situation. Lower levels of the abstraction hierarchy can be used to represent the local constraints associated with specific types of aircraft, instruments, levels of automation, or situational variables.

The Story Continues

“Forty-two!” yelled Loonquawl. “Is that all you’ve got to show for seven and a half million years’ work?”

“I checked it very thoroughly,” said the computer, “and that quite definitely is the answer. I think the problem, to be quite honest with you, is that you’ve never actually known what the question is.”

“But it was the Great Question of Life, the Universe and Everything,” howled Loonquawl.

“Yes,” said Deep Thought with the air of one who suffers fools gladly, “but what actually is it?”

A slow stupefied silence crept over the men as they stared at the computer and then at each other.

“Well, you know, it’s just Everything ... everything . . .” offered Pouch weakly.


The reader is probably expecting “the answer” to justify our long search for meaning. Unfortunately, we have no answer. We have generated several display concepts. Some are currently being evaluated in our synthetic task environment. But all are under revision, as we are not satisfied with any of our current displays. And quite frankly, although
we hope to ultimately produce some improvements to the representations in the cockpit, we don’t ever expect to get “the answer.” The search for meaning, like skill development, tends to be an asymptotic process – a small investment early yields large improvements – but continued progress comes at the expense of increasingly larger investments and no matter how much is invested there is always more to learn. Thus, we think it is a mistake to think of cognitive task analysis as an activity to be “completed” prior to design. Decisions about when to begin design or when a solution is good enough must take into account the practical, social, political, and economic constraints associated with the design project. However, the search for meaning does not end when a system is implemented.

An important challenge for cognitive task analysis is to integrate the cognitive task analysis into the work domain so that the system continues to evolve, to learn from mistakes, and to take advantage of new opportunities. Cognitive systems are dynamic, if they are not continuously learning/adapting, then they risk extinction. Meaning is a moving target! Currently, the only place that the evolving experience within a work domain is integrated and archived is in the memories of the domain experts. While some information can often be found scattered in manuals, texts, and case studies, these sources are rarely organized and collected in a way that allows easy integration and deep understanding. In 1991, Flach and Hansen developed a prototype for an interactive hypertext database for archiving data from a wide range of cognitive task analysis processes that could evolve over the life of a work domain. The database used Rasmussen’s (1986) abstraction hierarchy as a framework for structuring the database and for managing interactions (queries and additions) to the database. The database could be accessed from different levels of abstraction and the structure would guide inquires across levels of abstraction to help parse the domain into meaningful chunks and to reveal both the intentional (why?) and causal (how?) constraints within the domain. This project has never progressed beyond the prototype stage because the researchers were never able to find an organization willing to commit resources to the archival process.

People who are searching for simple, easy to understand answers will be sorely disappointed by the Cognitive Systems Engineering (CSE) approach. The search for meaning is not easy. It involves an iterative process of redefining the questions with no guarantee that answers will emerge. As far as discovering a great new interface for aviation – we are less confident now than we were at the start of our project. We hope that
this is because we are beginning to appreciate the depth of the problem. We think that we have a much deeper understanding of the domain – although we are far from consensus and there are still vigorous debates among the authors about how particular facts fit into the big picture.

This chapter only touches a fraction of the landing domain. For example, the design of approach plates is not discussed. These are “maps” of the approach landscape that incorporate all the computational richness reflected in Hutchins’ (1995) discussion of charts for ship navigation. The precision runway itself is another important artifact that has significant implications for the distributed cognitive processes associated with approach and landing. Also, little has been said about air traffic control and its role in the approach and landing. It is simply impossible to address all the important issues in the space of this chapter and the authors are still debating about whether we have chosen the right sample of issues for making our point.

One measure that gives us confidence that we are moving in a positive direction is the flavor of the interactions with the domain experts (i.e., pilots and aeronautical engineers). It is easier and (more enjoyable) to talk with either group and we find ourselves in a position to mediate between the two groups – e.g., helping pilots to appreciate “aeronautical theory” and helping aeronautical engineers to take a “pilot-centered” view of the control problem. There is clearly an aesthetic dimension to the search for meaning. Sometimes the joy of discovery, the beauty of a new way of representing the constraints, the comfort of feeling at home or the frustrations of conceptual dead-ends and the anxiety of being lost are the only indexes we have as measures of progress. Blind trust in these “measures” would be foolish, but when appropriately tempered with humble skepticism, the aesthetics of wonder may sometimes be the only guide in the search for meaning.

In describing our search for meaning in a book chapter, we are constrained to a linear narrative structure. However, it is important to realize that the search for meaning is not linear. All lines of investigation (reading about the history of aviation, talking to and observing pilots, talking to aeronautical engineers, flying and tuning the simulation) are all going on in parallel. It is hard to overstate the magnitude of the interactions across the various lines of investigation. For example, we can hear the same thing over and over again from pilots and not appreciate its meaning until we experience the problem flying the simulation or grasp a construct from aeronautical theory. In responding to design deadlines, some approaches can be more efficient than other –
tapping domain experts through interviews or field observations is typically the quickest way to learn about a domain and published sources and manuals are probably the most accessible sources of information. However, every source has its limitations, so it is important to seek input from multiple perspectives (Flach, 2000).

At times the search for meaning can be extremely frustrating as our first naïve answers to complex problems are crushed under the weight of new experiences. Although we don’t know what the answer is – we are better able to critique our ideas and to anticipate the limitations of any particular solution. We have a better sense of the space of plausible solutions. This provides an important benchmark that helps us to weed out weak hypotheses more quickly and to generate more compelling new hypotheses/designs.

So, the search for meaning is not likely to lead to “one best way,” but for now we are encouraged that we are taking small iterative steps toward a better, deeper survey of the landscape (the work constraints). As the figures in this chapter illustrate, we are experimenting with different ways to represent this landscape to ourselves with the ultimate goal of providing improved representations to pilots (i.e., interfaces and training protocols). At this point we are filled with wonder at the richness of the workspace and we are humbled by the gaps in our current representations of this landscape. On the other hand, we are amazed at the capacity of smart humans to consistently navigate successfully through the work constraints. It is the capacity of these smart humans that gives us hope to continue our own search for meaning.

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