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How Flying Got Smarter

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Abstract—**Most flying activities today are based on extensive knowledge, embodied in smart devices and algorithms to supplement and sometimes supplant pilots. Control developed in five principal stages. Initially flying was a pure *craft*, with high variability and low safety. In the 1930s, *rules* were developed, and instruments replaced human senses. Rule-based control proved inadequate to handle the complexity of WW II aircraft, and the result was the development of *standard procedures*. These three stages all used the human pilot to do the actual control. Two further stages use automated control. But higher stages of flying control revert to lower stages in some situations.**

I. INTRODUCTION

HUMANS have been flying for slightly more than a century. Originally, flying was a craft based mainly on personal sensorimotor skill. Only experts could do it safely, and the only way to become an expert was by brief apprenticeship followed by hundreds of hours of trial-and-error learning. Even experts often found themselves in situations they were unable to handle. Crashes occurred regularly

Today, most flying activity is a science. Commercial aircraft are highly automated, to the point that pilots normally limit themselves to high-level strategic decisions such as where to land, while the aircraft does its own minute-by-minute control.

Yet despite its advanced state today, there are still situations where flying must be done almost as it was in the 1930s. These occur when events are outside the "knowledge envelope." For example, there are no safe algorithms for controlling an aircraft covered with ice, and pilots are instructed to shift to manual control.

In this paper I trace flying through five stages of control, which I call Craft, Rules+Instruments, Standard Procedures, Automation, and Computer Integrated Flight.

Craft: From its invention in 1903 by the Wright brothers until the early 1930s, flying was almost entirely a craft activity. Pilots controlled airplanes by laboriously developed personal skill. Knowledge of what worked and why it worked was shallow, and developed almost entirely by empirical methods with little theoretical underpinning. Instruments were few, pilots used their senses for many measurements, and they flew in open cockpits to give their senses more raw material to work with.

Rules + Instruments: In the 1930s, flying was rule-based. Pilots were taught a list of rules about how to fly. The key to rule-based flying was reasonably accurate instruments. An example of rule-based flying was the ability to

fly inside clouds using an instrument called the *artificial horizon.*

Standard Procedures: In the 1940s, procedures came into play. Procedures are a formal sequence of activities, often based on conditional rules. Procedures go beyond rules because they supply a standard method for an activity, dictating all the steps and their order. Checklists are a simple form of procedure. Good procedures require considerable development.

Automation: In automated processes, an electronic system controls what happens, using real-time feedback. The earliest automation in flying was the simple mechanical autopilot. Pilots still decide when to activate automation, and monitor that it is performing correctly.

Computer Integrated Flight: This is "super-automation," which began in the 1980s. A suite of computerized subsystems jointly fly the aircraft.

Different flying activities are controlled at different stages. For example, it proved much easier to automate attitude control than engine control. So in the 1950s, a plane "on autopilot" could hold its altitude and course automatically, but the pilot was still responsible for setting the throttle. Conditions also matter: flying in bad weather is harder, so pilots operate at a lower stage than in ideal conditions.

TABLE 1
FIVE STAGES OF CONTROL IN FLYING

Stage of Control	Example of solved problem
Craft (up to 1930)	How to land; stall recovery
Rules (1930s)	Flying in clouds
Standard Procedures (1940s)	Complexity; human "care-lessness"
Automation (1950s)	Fatigue, limited attention
Computer Integrated Flight (1980s)	Controlled Flight into Terrain

Each stage constituted a paradigm shift, and had to be invented to deal with a problem that was insoluble using the tools available at previous stages. For example, standard procedures were needed to cope with the increasing complexity of larger aircraft. Previous stages did not become obsolete, however. Even today, some flying activities are done at each stage.

II. FLYING AS A CRAFT

A. Controlling an Airplane

Flying an aircraft encompasses a multitude of activities. They are often grouped into four categories, in decreasing

order of importance: *aviate* (keep the plane in the air), *navigate*, *communicate*, and *manage*.

The first requirement, which takes precedence over all others, is controlling the attitude of the aircraft, on a time scale of seconds, in order to keep it airborne on the desired flight path.

Fixed-wing aircraft have four primary controls including the engine. Unfortunately for novice pilots, the controls interact in complex ways, and because they work via the airstream, their effects vary depending on many variables, including air pressure, air speed, and aircraft weight. Pointing the nose up with the elevator can cause the plane to *lose* altitude, and using the rudder to steer without making any other changes will only cause the plane to move sideways. Flying an aircraft therefore depends on a high degree of feedback that can only be developed through practice.

One particularly dangerous situation is called *stalling*. In a stall, air speed over the wings is too low, and the wings abruptly lose lift. The result is a sudden loss of altitude. Reacting incorrectly will prolong the stall and increase the rate of descent with potentially fatal effects. All pilots are given practice in avoiding the conditions that cause stalls, detecting incipient stalls, and recovering from a stall as quickly as possible.

The most common cause of stalls is insufficient airspeed, for example from engine failure. The solution is to immediately push the nose down to gain speed. But this is the exact opposite of the instinctive reaction, which is to try to gain altitude! If the engine fails shortly after takeoff, for example, it is critical for the pilot to maintain airspeed by choosing a sufficiently steep glide. Attempting to postpone the inevitable descent by pulling the nose up just brings on a stall.

B. Learning Crafts

Controlling an aircraft by hand is taught today by practicing maneuvers under progressively more difficult conditions. There are four basic maneuvers: straight-and-level flight, turns, climbs, and descents. Maneuvers have to become automatic and "instinctive."

Part of the learning is developing a "feel" for the aircraft. Multiple senses provide the input, including noises from wind and engines, G forces, vibration transmitted through the airframe to the pilot's seat, and of course many visual cues. Feedback from the controls is important, such as the amount of force needed to move the control surfaces (rudder, ailerons, and elevator) against the airstream.

Novice pilots practice the four basic maneuvers until they can be performed with little conscious attention - they become what Rasmussen calls a *skill* [1]. As skills become more proficient, performance gets closer to the ideal. For example, in a perfect turn, altitude does not change from beginning to end. This requires the pilot to increase power and raise the nose while initiating the turn, and conversely when coming out of it.

Unfortunately, one of the properties of skill-based behaviors is that they do not adjust to different situations. For example when a pilot shifts into a different type of aircraft

his reactions will be "miscalibrated."

Just as different aircraft can throw off a pilot's skills, so will different flight conditions. Airplanes and their controls behave differently when gliding rather than under power. "Gliding maneuvers stand in a class by themselves and require the perfection of a technique different from that required for ordinary power maneuvers [2]." The FAA list of common errors when landing without power includes: "•Skidding or slipping during gliding turns due to inadequate appreciation of the difference in rudder action ... • Failure to lower pitch attitude during gliding turn entry resulting in a decrease in airspeed.... • Failure to maintain constant bank angle during gliding turns. •'Ground shyness'—resulting in cross-controlling during gliding turns near the ground." As if that were not enough, "A stall in this situation [cross-controlling] will almost certainly result in a spin," which at low altitude inevitably means a crash.

All pilots are given practice in recovering from a stall. But spins are so dangerous that flight instructors often don't even demonstrate them, much less have student pilots practice spin recovery.

Flying skills deteriorate without practice. Military pilots, for example, are expected to fly at least 30 hours per month. But this causes problems for pilots of today's automated aircraft. Their craft skills are not needed on normal flights. Yet in crises pilots must be ready to take control back from the automated systems.

C. A Fatal Flaw

On an evening in July 1999 John F. Kennedy Jr. spiraled his small plane into the Atlantic Ocean a few miles from his destination, killing everyone on board. The weather was good, but it was dark and he was flying over water. Other pilots in the area that night stated that haze obscured the horizon between sky and ocean. The most likely reconstruction of the accident is that Kennedy became disoriented while descending, unwittingly entered a bank that grew past 45 degrees, and entered a steep dive.

An FAA manual describes exactly the conditions that Kennedy encountered:

Night flying is very different from day flying and demands more attention of the pilot. The most noticeable difference is the limited availability of outside visual references. ... Crossing large bodies of water at night in single-engine airplanes could be potentially hazardous… *because with little or no lighting the horizon blends with the water, in which case, depth perception and orientation become difficult.* During poor visibility conditions over water, the horizon will become obscure, and may result in a loss of orientation. Even on clear nights, the stars may be reflected on the water surface, which could appear as a continuous array of lights, thus making the horizon difficult to identify [2].

Airmail pilots in the 1920s experienced a version of this problem whenever they flew into clouds. If they remained inside a cloud for even a few minutes, they ended up in a

spin. The issue was known as "blind flying." Before 1926, no one knew why this happened, and most fliers simply blamed it on insufficient skill among the unfortunate. Many airmail pilots preferred to fly under clouds, but this risked hitting trees or buildings, especially at night.

We now know that the problem was that our sense of orientation operates from three sensory systems. In blind flying they can seem to be working, yet be utterly wrong. One orientation method is based on seeing the horizon. The second and in normal life most important is the inner ear, which contains three fluid-filled vestibular canals. When our head rotates, gravity moves the fluid inside them. The third system is the "seat of the pants," i.e. pressure sensors in our skin.

Visual orientation requires a visible horizon, so it does not work in clouds. Yet the vestibular canals cannot distinguish *acceleration* from *gravity*. A pilot can be convinced he is flying flat and level, and yet be in a turn, or even a spiral. So human skills, without special instruments, keep the pilot oriented correctly only when the horizon is visible. Once a pilot in a cloud descends or turns, he loses his sense of orientation. The aircraft will gradually deviate from straight and level flight, but the pilot's senses will insist that everything is fine. Eventually, the aircraft will stall, often with a spin.

The mail pilots found these spins frustrating because they could not explain the phenomenon. Beginning in 1926 two army officers, pilot Captain William Ocker and flight surgeon Major David Meyers, began a campaign to convince pilots that the error lay in believing that people could fly using their sense of balance. They ran experiments using a rotating chair to simulate motion.

> After only a few minutes, the difference between what a pilot thought the plane was doing and what it was actually doing became so great that the pilot lost control. In reality, as the gap between apparent and actual motion grew, pilots began to overcontrol, eventually making too tight a turn and stalling the plane which in turn caused a spin. Between 1927 and 1932, when Ocker and army pilot Carl Crane published their full study in a highly influential book, they tested a large number of mail, airline, and army pilots to find that only 3 percent could fly blind [3].

It would be hard to come up with a clearer example of the problem with craft. Pure craft methods, based on skills learned by experience, worked when the weather stayed fine. But when it turned bad, pilots flying cross-country could end up in the clouds where personal skills, no matter how well developed, could kill them. The only solution was to move to the next level of technology, one based on rules and instruments.

III. RULES, INSTRUMENTS, AND PROCEDURES

The solution to the blind flying problem was a gyroscope-based instrument called the *artificial horizon*, now called the *attitude indicator*, which shows an artificial horizon inside the cockpit. But its use was counter-intuitive, and pilots

"tended to believe that the turn indicator and artificial horizon worked fine as long as they could see, but once in the clouds they thought the instruments went haywire and reported turns that the pilots were certain the airplane was not making. .... *Pilots had to be broken of their dependence on their sense of balance* [3]."

When flying in bad conditions, the intuitive approach had to be unlearned and replaced by a method using specialized instruments and a more systematic rule-based approach to flying. Today, pilots have a suite of instruments for blind flying (now called *instrument flying*). The key rule they must follow in clouds is "when senses and instruments conflict, believe your instruments."

A. Additional knowledge required for rules

Devising successful rules requires several kinds of knowledge. The rules themselves are *control knowledge*, also called *procedural knowledge*. But they have to be based on *causal* knowledge, also called *declarative* knowledge. The cause-effect relationships between actions and results need to be known explicitly in order to develop the rule.

In addition, rules require appropriate *measurement tools*, known in aviation as *instruments*. These tools replace the senses of an expert by a number, or at least an ordinal measurement. Without them, most rules could not be taught because there is no vocabulary to specify them, and no way to communicate to a newcomer what they mean except through learning-by-doing.

Each instrument required pilots to learn how to deal with malfunctions, including causes and how to prevent them, how to recognize them, and how to respond. For example several instruments, including airspeed and altimeter, rely on an external air stream, which can be partially blocked by ice, dirt, insects, or other causes. Under these conditions, an elaborate set of rules specifies which instruments can and cannot be relied on, and use of workarounds [4]. Anomalies involving these instruments still occur, and may have been involved in the unsolved crash of Air France AF-447.[5]
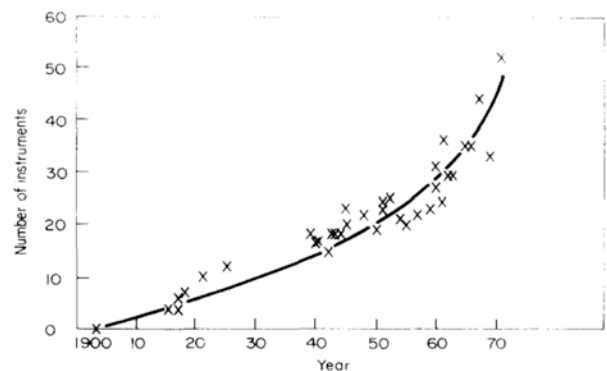
Fig. 1 Cockpit instrument growth of fixed wing, single seat fighters [6]

B. Standard Procedures

The complexity of flying increased considerably over time, as aircraft became more sophisticated, new navigation techniques were developed with their own instruments, and

backup systems added. A reasonable measure of complexity is the number of instruments and controls that pilots were expected to monitor, understand, and use. The number of instruments rose dramatically in WWII, and again in the 1960s. (Fig. 1) Multi-engine commercial airliners had even more instruments and controls. (Fig. 2)

The solution to this complexity was formal standardized procedures. The simplest procedures are just lists of rules in particular sequences, "Do A, Do B, Do C". Yet the difference from rules is important. Without a standard procedure, the pilot must remember all the rules, and invoke the appropriate rule at the right time. As complexity of controls and instruments increased, the cognitive load on pilots increased, and so did the number of errors.

The aviation checklist, the first version of standard procedures in aviation, was invented in 1935 when the US Army was testing Boeing's prototype four engine bomber, which later became the B-17. On a test flight with the Air Corps' chief test pilot at the controls it took off, rose to 300 feet, stalled, crashed, and burned. "Investigators determined that the Fortress had crashed because the elevator and rudder controls were locked—the pilot could not lower the nose, so the aircraft quickly stalled. Ironically, the elevator locks had only been recently installed as a safety feature, to protect the control surfaces from moving about on the ground and being damaged during high winds. The locking mechanism was controlled from inside the cockpit, but no one remembered to disengage it before takeoff [7]."

F

Fig. 2   Forward cockpit of VC—10 aircraft

The accident forced Boeing and the test team to find a way of avoiding such oversights in the future. They came up with the concept of a checklist "that spelled out specific tasks that were to be accomplished by each crew member at various times throughout the flight and also while on the ground." Today every pre-takeoff procedure includes moving the controls in the cockpit while visually checking that the appropriate control surface moves.

Procedures have important benefits beyond making complex situations more tractable for flight crews. They allow rapid dissemination of new techniques, they facilitate training, and they constitute a body of knowledge that can be studied, experimented on, and systematically improved.

IV.   AUTOMATION AND OPTIMIZATION

Even with procedures, piloting was limited by the processing ability of the human mind and the speed of the human nervous system. As the number of instruments and controls increased, one approach was to add more crew, in some cases up to five specialists: pilot, copilot, engineer, navigator, and radio operator. (Fig. 3) Adding crew to planes increased weight and cost and reduced performance. Furthermore, rising speeds required faster reaction times than people could provide consistently.

Fig. 3 Flight Engineer on VC-10 commercial jet (courtesy G. Hall)

The solution was automation: artificial systems to handle specific and well-understood tasks. The first automation was the autopilot, which kept an airplane flying in a straight line without a pilot's hands on the controls.

Mechanical autopilots were expensive and difficult to maintain. In the 1950s airborne electronics became feasible, and were used for both instruments and simple feedback control loops.

Automation works only if there is sufficient formal and explicit knowledge. The fundamental concept of procedures is still at work but they are now carried out by computers or other artificial devices. Automation requires even more knowledge to carry out the equivalent procedure. Eyes and hands must be replaced by sensors and actuators, so successful automation requires development of good sensors. More fundamentally, automated control must be specified in much greater detail than for a person, and is less robust in unanticipated situations.

A.   Case Study: Controlled Flight Into Terrain

Controlled Flight into Terrain is an aviation expression for a particularly deadly kind of accident. The aircraft is flying normally, but seemingly without warning it runs into a mountain or other terrain. As with virtually all crashes, an accumulation of errors by different players is usually responsible. But in the final moments, the pilots could often have averted the crash by an emergency climb maneuver.

In 1979 Air New Zealand Flight 901, a sightseeing flight to Antarctica, crashed into a 13,000 foot volcano. The plane was flying under computer control at the time, along a programmed flight path that was 20 miles away from the one the crew believed they were on. The navigation system controlled the horizontal coordinates; altitude was controlled by the pilots. Believing the ground was obscured by clouds, the pilots descended below 2000 feet. Actually, they were in a condition known as "whiteout" which obscured the boundaries between air and land. Mount Erebus was directly in front of them, yet not recognized. Everyone on board was killed instantly [8].

In response to CFIT accidents, the FAA began to require warning devices, and today *Enhanced Ground Proximity Warning Systems* are standard on military and commercial aircraft. The earliest version of these systems (called GPWS hereafter) used a radio altimeter. An analog circuit looked at the rate of closure between the aircraft and the ground, and if it was too fast set off a warning siren and light [9],[10].

This seemingly simple idea - warn pilots when they are about to hit the ground - takes a considerable amount of detailed knowledge to make it work. Knowledge evolves both incrementally through refinement of a single basic idea, and discontinuously through addition of entirely new approaches.

A fundamental issue in designing a GPWS is deciding whether to sound an alarm, and how quickly to sound it. Conservative criteria sound alarms when there is a possibility of danger many seconds in the future, but this leads to a lot of false alarms. False alarms cause crews to take unnecessary evasive action, which can itself be risky. They also reduce the credibility of subsequent alarms, leading the crew to be slower in responding while they try to figure out if the problem is real [11]. On the other hand, waiting too long to sound an alarm gives pilots insufficient time to respond. Commercial flights still have CFIT accidents, and in 28 percent of the cases from 1988 to 1995 the GPWS sounded no alarm at all [10].

Each "mode" therefore requires a set of decision rules about when to sound an alarm. For example, mode 2A sounds an alarm as a function of altitude and terrain closure rate. But when the aircraft "intends to land," this would sound too many alarms, so mode 2B is activated instead. The GPWS "decides" when to switch modes based on whether the flaps are down and other criteria. It used Mode 2B for 60 seconds after takeoff; in addition a third warning mode is activate for the first 1500 feet of altitude after takeoff to make sure the aircraft continues to climb. In short, the GPWS had a number of decision rules that had to be developed, tested, and implemented. Over time, decision rules became more complex (Fig. 4).

B. Problems with Automation

Automation is essential to achieve the performance and safety levels of contemporary civil aviation, but it created at least three new classes of problems. The anticipated problem was that of reliability. A second, unanticipated, problem was

that *interactions* between automated systems and the pilots began to cause accidents. The third problem, also unanticipated, was that pilots' primary roles shifted from "aviating" to "managing," which has many undesirable consequences.
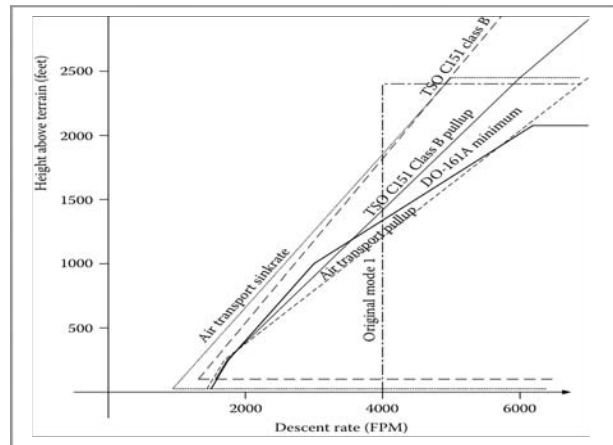

Fig.4 Increasing complexity of ground proximity warning rules [9].

Reliability has been addressed through careful design, using many methods to avoid failures, recover from failures, or mitigate their effects. Startup checklists include a variety of tests of electronics, hydraulics, and other control elements, usually using built-in self test. Triple-redundancy of instruments, computers, data buses, actuators, and cockpit displays is routine, and often one system will use completely different hardware and software. Systems are designed to fail gradually, such as Airbus' multiple "control laws [12]."

Automation introduced new types of failures. Pilots must monitor the behavior of automated systems and be ready to take over in case of conditions outside their design parameter. But when an aircraft behaves "oddly," is it due to a physical problem, to the automated system attempting to deal with a problem, or to the automation itself? "Previously, most accidents were caused by problems with the physical skills involved with flying the aircraft, or through errors of judgment. The new problems involve issues of management of the complex aircraft and associated automation systems. The role of the pilot has shifted from being a manipulator of the controls to be a manager of aircraft systems. Within the set of errors attributed to flight crews, automation problems are emerging as a key safety area [13]."

The increasing sophistication of these systems aggravates some of these issues. Many problems arise from the multitude of "modes," in which the same behavior by pilots can have dramatically different effects. For example, adjusting the throttle could lead to the autopilot shifting from one mode to another, or the throttle change could be overruled by the autopilot, or it could adjust the engine speed.

C. Computer Integrated Flight stage

Flying has now advanced to a second stage of automation, characterized by programmable software algorithms, multi-sensor integration, and of digital control. I refer to this as the

Computer Integrated Flight stage. Control is handled by a variety of loosely integrated subsystems.

But contemporary systems also provide an entirely new level of warning, called "Enhanced" Ground Proximity Warning System. In essence these systems contain a 3-dimensional model of the world which they use as a "virtual radar" that looks ahead of the aircraft and warn of approaching problems far before any on-board sensor could detect them. Furthermore, they show a continuous real-time contour map of approaching terrain, with color codes to indicate terrain at different altitudes. (Fig. 5) The map also shows pilots how to take evasive action.

Fig. 5 Sample terrain display from enhanced warning system [14]

Once the system carries a 3-D "map," additional information can be added. Honeywell, for example, reports that its navigation database has 80,000 man-made objects such as radio towers, coded with location and height.

Another example of Computer Integrated Flight is sophisticated navigation with multiple modes for horizontal and vertical control. These systems can optimize speeds and climb profiles to minimize fuel consumption while hitting 4-dimensional waypoints (location, altitude, and time). Fuel management systems can actually improve performance by shifting fuel to properly trim the aircraft as a flight continues.

V. CONCLUSION

The evolution of flying from 1900 to the present has parallels in other technologies. Manufacturing went through analogous stages, from crafts before 1800, to computer-integrated manufacturing today [Table 1]. In both technologies, the development of measurement methods was necessary to move beyond craft, the development of manual standard procedures was critical, and digital computing provided unprecedented levels of speed and precision of control. Flying may be unlike manufacturing in the degree to which all control stages are still taught and used. This may be to be due to the greater flexibility of lower control stages, which is important when an aircraft encounters unanticipated or poorly understood conditions. (Icing, hijacking, major mechanical failures, etc.)

One of the key long-term causes of flying safety is sys-

tematic techniques for learning from collective experience. The safety system in the US includes the National Transportation Safety Board (NTSB) which investigates accidents, and the Federal Aviation Administration which independently regulates pilots and airlines. NASA runs an anonymous safety reporting system that encourages pilots to report safety-related problems that did not, but might have, led to accidents. Vendors such as Honeywell and Boeing collect event data from built-in logging and maintenance reporting systems, and use them to identify previously unknown problems and to refine algorithms. Software changes, hardware fixes, new procedures, and advisory information are then broadly disseminated. This contrasts with practices in the auto industry, as suggested by the recent problems with electronic controls at Toyota.

TABLE 1
EVOLUTION OF FIREARMS MANUFACTURING [15]

The Craft System (circa 1500)
Machine tools and the English System of Manufacture(1800)
Special purpose machine tools and interchangeability of components in the American System of Manufacture (1830)
Scientific Management and the engineering of work (1900)
Statistical process control in an increasingly dynamic manufacturing environment (1950)
Information processing and the era of Numerical Control (1965)
Flexible and Computer-Integrated Manufacturing (1985)

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