NASA/TM—2005-213978

Propulsion Control Technology Development in the United States

A Historical Perspective

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October 2005

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Acknowledgments

We would like to express our gratitude to many people who have helped to gather information and review the draft: Former chiefs, Controls and Dynamics Branch, NASA Glenn: Walter Merrell, Carl Lorenzo, and Fred Teren; Ten-Hui Guo, Khary Parker, Lynn Anderson, and Bonita Smith, NASA Glenn; Bill Burcham, NASA Dryden; Charles Skira and Al Behbahani, Air Force Research Laboratory, Wright-Patterson Air Force Base; Harold Brown and Kiyoung Chung, General Electric Aircraft Engines; Al Levesque, Ramesh Rajagopalan, Matthew Schryver, Dale Southwick, Alan Volponi, and Bruce Wood, Pratt & Whitney; Glen Schwent, Robert McCarty, and Larry Yee, Honeywell Engines; and Hatti Wong, Scientific Monitoring, Inc.

This paper is dedicated to all those who have contributed to the advancement of air-breathing propulsion control capabilities in the world.

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Abstract

This paper presents a historical perspective of the advancement of control technologies for aircraft gas turbine engines. The paper primarily covers technology advances in the United States in the last 60 years (1940 to 2002). The paper emphasizes the pioneering technologies that have been tested or implemented during this period, assimilating knowledge and experience from industry experts, including personal interviews with both current and retired experts.

Since the first United States-built aircraft gas turbine engine was flown in 1942, engine control technology has evolved from a simple hydro-mechanical fuel metering valve to a full-authority digital electronic control system (FADEC) that is common to all modern aircraft propulsion systems. At the same time, control systems have provided engine diagnostic functions. Engine diagnostic capabilities have also evolved from pilot observation of engine gauges to the automated on-board diagnostic system that uses mathematical models to assess engine health and assist in post-flight troubleshooting and maintenance. Using system complexity and capability as a measure, we can break the historical development of control systems down to four phases: (1) the start-up phase (1942 to 1949), (2) the growth phase (1950 to 1969), (3) the electronic phase (1970 to 1989), and (4) the integration phase (1990 to 2002). In each phase, the state-of-the-art control technology is described and the engines that have become historical landmarks, from the control and diagnostic standpoint, are identified. Finally, a historical perspective of engine controls in the last 60 years is presented—in terms of control system complexity, number of sensors, number of lines of software (or embedded code), and other factors.

1.0 Introduction

The year 2003 commemorated the 100th anniversary of the Wright brothers' flight—the first *powered* flight, where both the airplane and the engine were designed and built by the Wright brothers. This first powered flight sparked enthusiasm about aviation around the world leading to development of a mature industry that has revolutionized transportation. In the past 100 years, aviation has become a symbol of innovation with record-setting breakthroughs, many of which have been contributed by advances in engines or propulsion systems. During this period, propulsion systems have evolved from piston engines (the first generation, 1903 to 1945) (Ref. 1) to jet engines (1942 to present) (Refs. 2 and 3). This paper provides a historical perspective of the development of jet engine control technologies; specifically, it focuses on the technical advancements of turbofan and turbojet engines in the United States during the past 60 years. This historical period is further divided into four controls developmental phases as follows:

(1) Start-up phase, 1942 to 1949
(2) Growth phase, 1950 to 1969
(3) Electronic phase, 1970 to 1989
(4) Integration phase, 1990 to 2002

In each phase, a brief description of the key technologies is first presented, then the engines that have made historical contributions are tabulated. Section 6 presents a global view of the evolution of the controls technologies in the last 60 years. Before we look back in history, a brief review of the gas turbine engine control principle may be helpful.

A simple engine control system computes the amount of fuel needed for the engine to produce a desired power (or thrust), based on pilot's power request through a throttle (or a power lever); then it meters the right amount of fuel to the engine's combustion chamber(s); and it maintains the engine power at the desired level in the presence of air flow disturbance and changes in flight conditions. Figure 1.1 illustrates this *fuel* control system and identifies the various components needed to make the system work.

The valve is usually called an *actuator*, whose position changes with the fuel flow command, and the fuel flow is called a *controlled variable*.

If we change "power" in Figure 1.1 to "turbine temperature," then the process represents a temperature control system, or a temperature governor. Likewise, if we change both "power" and "fuel flow" to inlet guide vane angle (IGV), then the diagram becomes an IGV control system.

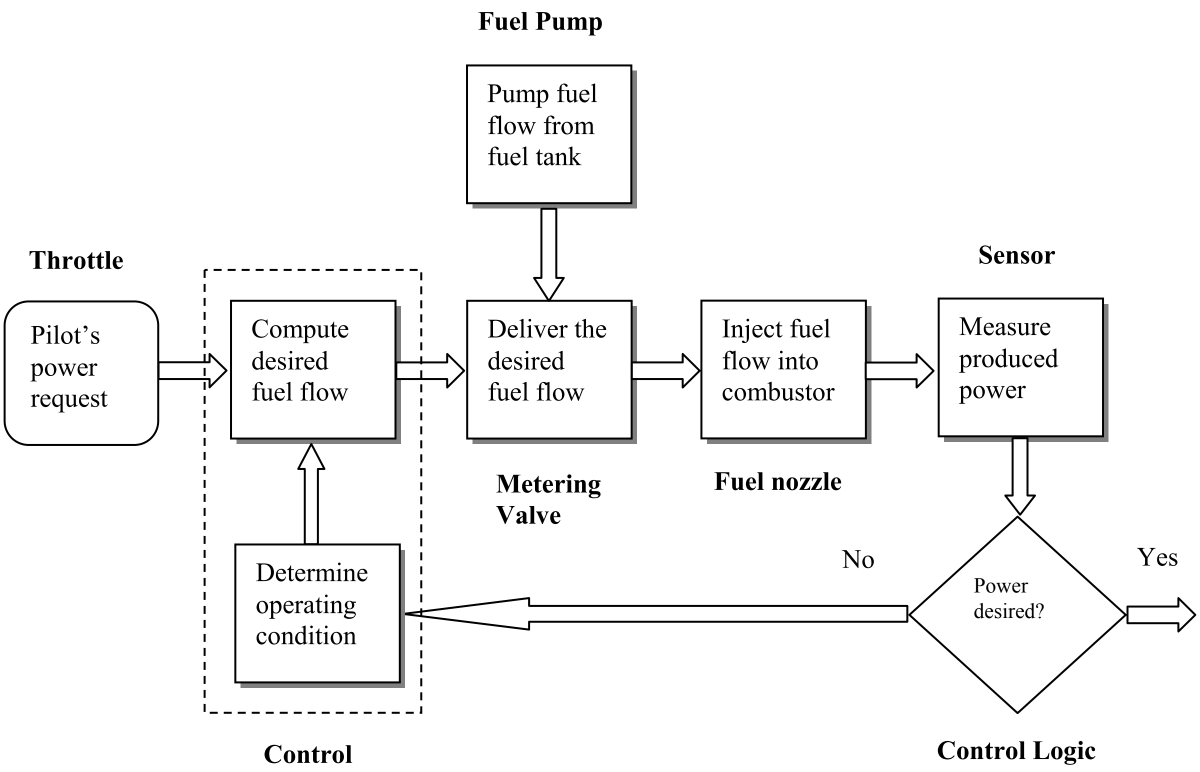

Figure 1.1.—Functional process diagram of a simple engine control system (from Ref. 2).

In-flight engine thrust measurements are not possible. Good indicators of thrust can, however, be obtained from either engine shaft rotational speed (N) or engine pressure ratio (EPR) and these parameters have been used effectively in the engine control process.

An aircraft engine is designed to operate in a wide operating envelope (to support aircraft mission profiles). Typically, the altitude can vary from sea level to 50,000 ft (or even higher), the air speed can go beyond Mach 3; furthermore, the air temperature at the same altitude and airspeed can vary from a hot summer day to a cold winter night. These ambient condition variations have imposed severe challenges on control system design. To a control engineer, these challenges are represented on a fuel flow (Wf) versus engine shaft speed (N) graph, or a fuel ratio unit (Wf/P3, where P3 is the compressor exit static pressure) versus speed graph, as shown in Figure 1.2.

After engine start, the engine operating envelope (shaded in light green) is bounded by the maximum flow limit, the minimum flow limit, the idle power governor and the maximum power governor. The ‘max. flow limit’ prevents the engine from surge and over-temperature. The ‘min. flow limit’ prevents the engine from flame-out. The idle power is typically set to produce a desirable ground thrust for taxiing the airplane, and the max. power produces the engine maximum-rated thrust. The max. and min. flow limits are also called the acceleration and deceleration schedules. These schedules change with the engine ambient condition.

The figure also shows four straight lines intersecting the idle power point and the max. power point on the steady state operating curve. These lines are called droop lines, which represent the proportional control gains ($\Delta Wf/\Delta N$) at the two power points, respectively. In reality, the trajectories between a power set-point (e.g., idle or maximum) and a fuel control limit (either the max. limit or the min. limit) is not a straight line, because all engine fuel controls use at least one additional control law, the integral control, to improve control system robustness. Many modern engines use derivative control and complex control compensations to shape the transient performance.

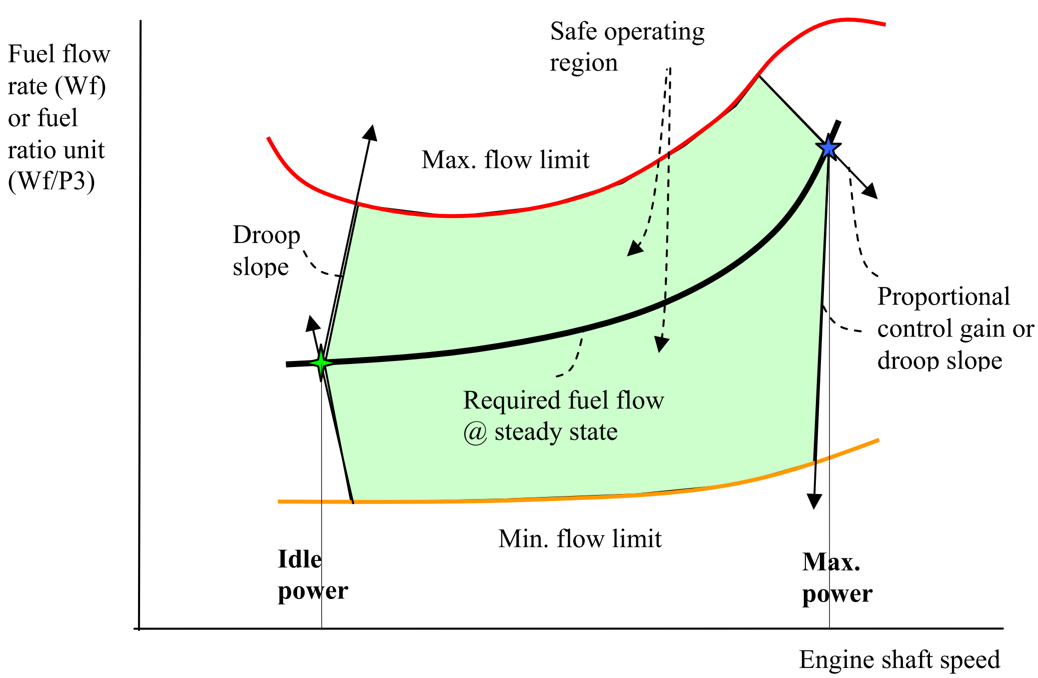

Figure 1.2.—Gas turbine engine fuel control system operating envelope.

Additional limit-protection capabilities are provided in engine controls, such as the temperature limiting governor, the over-speed governor, and the stator vane scheduler. These additional limit protections together with the basic control schedules are designed to support unrestricted throttle movement by the pilot. Consequently, the time history of the fuel flow controlled variable of a jet engine is characteristically nonlinear.

2.0 The Start-up Phase (Before 1950)

2.1 Control System Description

The first U.S. jet engine was built in 1942 by General Electric (GE). This engine, GE I-A, was designed after the British Whittle turbojet engine. The control for the GE I-A was a hydro-mechanical governor, which metered the fuel flow going into the engine to be proportional to the difference between the set speed and the actual speed of the turbine. To prevent the engine from flame-out, a minimum-flow stop was added to the fuel metering valve. To prevent the engine from over-temperature, a maximum-flow schedule was also incorporated. This system possessed the basic functionality of controlling a single-spool turbojet engine.

In 1948, GE tested the first afterburning turbojet engine in the world, the J47. The engine incorporated a hydro-mechanical fuel control for the main combustion chamber, and an electronic (vacuum tube) fuel control for the afterburner; unfortunately, the reliability of the electronic control was poor due the problem-prone vacuum tube technology in a harsh operating environment like a jet engine.

2.2 Control Design Methodology

The original control law for the J47 was designed using only frequency response techniques. The engine underwent altitude testing at NACA (National Advisory Committee for Aeronautics) Lewis Laboratory (now NASA Glenn Research Center). During the testing, it was found that the noise in the speed sensor, coupled with the high gain of the speed governor, caused the engine to behave like a limit cycle. To solve this problem, GE and NACA engineers worked together and applied the time-domain step response analysis method. The problem was soon fixed by reducing the control gain at altitude (Ref. 4). This industry-government cooperation experience has established a good foundation for building a knowledge base for engine controls.

2.3 Modeling Capability

Engine steady-state performance was obtained from cycle calculations using component performance maps derived from component test results, constant specific heat gas properties, and an iterative process for balancing internal engine flow and energy transfers. Since each engine operating point could take several hours by slide rule or desk calculator, corrected parameter techniques (corrected flows and speeds, temperature ratios, and pressure ratios) were used to reduce the number of operating points which needed to be evaluated to define engine operation over the engine's operating envelope. The corrected parameter approach was derived from dynamic similarity techniques based on the Buckingham π-theorem. This corrected parameter approach is still in use today as it simplifies the process of control law development and implementation.

Dynamic behavior of single-shaft turbojet engine was studied at NACA Lewis Laboratory in 1948. The study focused on the dynamics of the shaft speed, because it is almost analogous to thrust and can be more easily and more accurately measured. The study showed that the dynamic characteristic of a turbojet engine, i.e., the transfer function from fuel flow to engine speed, can be represented by a first-order lag linear system with a time constant (Ref. 5).

3.0 The Growth Phase (1950 to 1969)

3.1 Control System Description

In 1951, Pratt & Whitney (PW) flight-tested the first two-spool turbojet engine in the world, the J57, and achieved supersonic speed on a YF-100. The control system of the J57 consisted of a hydro-mechanical fuel control (HMFC or HMC) for dry-engine combustion chambers, a HMFC for the afterburner, and separate anti-ice and ignition controls.

As engine capabilities advanced in the 1950s, engine control technologies also accelerated to deliver the new capabilities. By 1969, a number of well-known and long-service engines had been tested, such as GE's J79 and F101, and PW's TF30 and F100. As the engine technology had matured to high compression ratio, by-pass flow *turbofans* during this period, the control technology had also matured to variable geometry controls, e.g., the compressor stator control, intake and nozzle controls. This period exemplified several successful transfers of military engine technologies into commercial engines (Refs. 6 and 7). The most notable examples are the PW JT3 (originated from the J57) for the Boeing B-707 and the Douglas DC-8, PW JT8D (from the J52) for the B-727 and the DC-9, PW JT9D (from the TF30) for the B-747, GE CF6 (from the TF-39) for the DC-10, and CFM56 (from the F101) for the B-737-300.

3.2 Control Design Methodology

Control designs during this phase were predominantly the frequency response method through which the gain and the phase margins were analyzed as the leading design parameters for closed-loop system stability. The step response method was also used to assure stability and performance in the entire operating envelope. Successive loop-closure was the technique used invariably in the industry to decouple the effects among multiple controlled variables.

The early 1960s marked the birth of the modern control era. Linear state-space methods provided a new paradigm for modeling, control, and estimation (Ref. 8). The multivariable control design method became an intellectual pursuit, although the traditional single-input, single-output (SISO) approach and the frequency response design method were used for all production engines. Although theoretically matured in the 60s, the modern control design paradigm did not find its way into the turbine engine industry until mid-1970s, and the first implementation of a multivariable-control-designed engine did not happen until almost 30 years later.

3.3 Modeling and Simulation Capability

The first computerized, component-level, steady-state engine performance model was developed in 1953 for constant specific heat gas properties. It was extended to actual variable gas properties in 1955, and from turbojet to turbofan engines in the late 1950s.

Initial development of simulations of the dynamic performance of gas turbine engines was achieved through the use of electronic analog computers at NACA Lewis in the early 1950s. During this time, the response of a turbojet engine to a step change in fuel flow was simulated and the results were validated by experimental results (Ref. 9).

A more efficient numerical solution, commonly called the balancing or matching technique, or more theoretically, the Newton-Raphson method, for component-level, steady-state engine performance models were developed in the mid-1960s by the Air Force Aero Propulsion Laboratory (AFAPL). This new solution technique significantly reduced the time to compute a design point from weeks to days (Ref. 10).

By the mid-60s, 90 percent of the work involved in dynamic (or transient) performance analysis, which was essential for control system design, was already handled by either analog or digital computer analysis, while the remaining 10 percent was handled by hand analysis. Almost every known jet engine transient was analyzed through simulations. A dynamic simulation typically consisted of engine models and control system models connected in closed-loop. The analysis typically included frequency response, transient response, large accelerations and decelerations, starting cycles, afterburner light-off and shut-off, compressor stalls, and combustor blow-out (Ref. 11).

4.0 The Electronic Phase (1970 to 1989)

4.1 Control System Description

As engine control functionality expanded, control system complexity also increased. Control complexity is reflected by the number of controlled variables managed by a control system. As control complexity increased, the traditional hydro-mechanical fuel control and servo components, although having been proven as highly reliable, were quickly reaching a practical limit, i.e., they became increasingly bigger, heavier, and more expensive to be practical for aircraft engine controls.

In the early 1970s, analog and digital electronic control units (ECU) were designed to provide high-level supervisory or trim functions. These *supervisory* control units primarily calculated speed or temperature set-points throughout the engine operating envelop. For some non-critical controlled variables, they would have sole control responsibilities. Early production supervisory control units included: the digital Electronic Engine Control (EEC) unit for the PW F100 and the analog Augmentor Fan Temperature (AFT) control for the GE F101. The F100 EEC is the first supervisory control for aircraft engines.

An ECU is considered *full-authority* if it controls the entire operation of an engine from start-up to shutdown according to pilot's throttle command (or power request). The first full-authority ECU was introduced into service in 1972 on the Garrett/Air Research (now a division of Honeywell) TFE731 engine. The TFE731 ECU was a single-channel *analog* control. In case of a failure or pilot over-ride, the electronic control switched to a back-up HMC with conservative, fixed fuel-ratio max. and min. schedules. The electronic control provided the following key functions (Ref. 12):

(1) Minimal pilot attention and fail-safe operation.
(2) Unrestricted power lever movement, i.e., the electronic control computes all control schedules, power setting, and engine operating limits.
(3) No throttle dead-band.
(4) Maximum power lever always gave the maximum allowable thrust.
(5) Automatic flat rating for thrust.
(6) Rapid surge-free acceleration through a modulated on-off bleed valve.

Improving the mean time between failure (MTBF), especially for a given mean time between unscheduled removal (MTBUR), and the ease of field maintenance were the prime motivations behind the initial transition from analog to digital controls. Other advantages were quickly discovered and set the trend for digital electronic controls such as the flexibility of the digital software for complex computation and software revision, the capability of fault isolation to LRU (line replaceable unit) level through self-testing, and simplified and more accurate control adjustments.

The F100 DEEC (Digital Electronic Engine Control) was the first full-authority digital electronic control (FADEC) that was flight-tested. The DEEC evolved from the supervisory EEC of the F100 engine HMC and from a digital electronic breadboard for automating the design of the cam schedule used in the HMC. This electronic breadboard significantly reduced the development time from months to weeks, demonstrating the capability of electronic controls to improve the overall engine development cycle time.

During the past 30 years, the ECU has proven the following undisputable benefits:

(1) Significant size and weight reduction for the same control functionality.
(2) Unrestricted power lever movement, especially in military applications, thus reducing pilot workload.
(3) Elimination of engine trim after any control component change.
(4) Easy software update (through a laptop computer).
(5) Compatibility with flight control, fire control, and other on-board and monitoring systems.
(6) Power to record engine data. Better maintainability due to increased diagnostic capabilities from electronics (fault flags and fault isolation).

4.2 Control Design Methodology

The trend in this phase was the multivariable control design method. Although a lot of interest was shown in advanced control design technologies; however, all production engine controls were still designed by SISO and successive loop-closure techniques. Multivariable control design methods had gradually matured during this phase since the early 1970s. Both frequency-domain and time-domain methods were studied extensively (Ref. 13). Frequency-domain methods were led by the Inverse Nyquist Array (INA) method (Ref. 14). Time-domain methods were led by the Linear Quadratic Regulator (LQR) method.

In the area of time-domain control design, the United Aircraft Research Laboratories (now the United Technologies Research Center) appeared to be the first to apply a modern control design method, or more specifically, the LQR design, to an aircraft engine (Ref. 15) in early 1970s. The U.S. Air Force Wright Aeronautical Laboratory (AFWAL, now the Air Force Research Laboratory) started to apply multivariable control design methods to a J85 engines in 1973 (Ref. 16). AFWAL and NASA Lewis then jointly sponsored the Multivariable Control Synthesis (MVCS) program from 1975 to 1978. The program developed a series of LQRs and connected them with simple transition logic and several operating limits to achieve effective large-transient controls. The control design (Ref. 17) was verified extensively at NASA's hybrid simulation facility (Ref. 18), and followed by a successful testing on an F100 engine in NASA's altitude test facilities (Ref. 19).

The multivariable control methodology lends itself to complex, integrated control problems. One of these problems is the integrated flight and propulsion control (IFPC). IFPC relieves pilot workload and improves aircraft maneuverability. Improving maneuverability can be achieved by thrust vectoring and jet diversion. In the mid-1980s, AFAPL sponsored the DMICS (design methods for integrated control systems) program to study different design methods. The natural approach was to combine the flight control and the propulsion control into one integrated system and to design an integrated control law for the combined system. This approach had some practical concerns: (1) airframe and engine manufacturers traditionally design their control systems separately before system integration, and (2) early and close coordination and cooperation between flight and propulsion system designers could drive the design cycle longer (hence cost). A less intuitive approach was to treat the IFPC control design problem as a hierarchical, de-centralized system and integrate the functions of the flight and propulsion subsystems through cross-coupling effects and flight command translation (Ref. 20).

4.3 Modeling and Simulation

By early 1970s, steady-state and transient performance simulations (commonly called the steady-state cycle deck and the transient cycle deck, respectively) of jet engines were routinely used in engine and control system designs. Furthermore, the combined cycle deck proved effective in improving engine test quality by ensuring engine and test cell compatibility, reducing test requirements, and extending the knowledge of the engine performance (Ref. 21).

In the early 1980s, NASA Lewis initiated an effort to build an engine real-time simulator. The simulator consisted of both hardware and software. The hardware was designed with parallel, multi-processors. The software included a high fidelity, aerodynamic model of a turbofan engine. At the same time, an integrated real-time simulation of V/STOL (vertical/short takeoff and landing) aircraft was developed, combining both airplane and engine simulations models and setting the foundation for integrated flight and propulsion control studies (Ref. 22).

4.4 Failure Detection, Isolation, and Accommodation (FDIA)

In 1970, the F100 was the first engine equipped with an on-board event history recorder (EHR). This recorder was the predecessor of the engine diagnostic unit (EDU) installed on later models of the engine in 1980s. The EDU and the DEEC together perform the engine monitoring system (EMS) function. The EMS provides the user with information on engine condition and engine life usage data. The engine condition data is used to isolate faulty components or systems during engine troubleshooting. The DEEC continuously performs integrity test on itself and system signals (i.e., built-in test, BIT). These tests enable the DEEC to detect and accommodate system malfunctions while maintaining normal engine operation. The DEEC transmits diagnostic information and selected control parameters to the EDU to identify control system faults and facilitate data recording. The EDU detects engine events, records data, and handles engine-airframe communication. The EDU also receives data through the engine-airframe interface and engine sensors. This information permits the EDU to record engine data and perform fault detection independent of the DEEC (Ref. 23).

The initial success in applying multivariable control design methods to jet engines in the mid 1970s prompted the AFWAL to explore failure detection and accommodation techniques (Ref. 24). In early 1980s, motivated by improving the reliability of FADECs, NASA Lewis explored the analytical redundancy approach to sensor failure detection, because the engine sensor is one of the least reliable control components. NASA later conducted a real-time simulation of an advanced detection, isolation, and accommodation algorithm for sensor failures using analytical redundancy. The simulation demonstrated the feasibility of real-time detection and accommodation of both large-magnitude (or hard) and small-magnitude (or soft) failures (Ref. 25).

4.5 Flight Research and Advanced Control

Propulsion flight research with the purposes of investigating engine control-related problems and testing new control concepts began in late 1960s as a joint effort between NASA and U.S. Air Force. Since that time, propulsion flight research has been conducted at Edwards Air Force Base and the NASA Dryden Flight Research Center in Edwards, California (NASA Dryden), with some level of support from NASA Glenn. The U.S. Air Force asked NASA in 1973 to assist in developing and flight-testing a digital IPCS (Integrated Propulsion Control System). The IPCS, installed on an F-111E airplane, was the first flight test of an integrated engine control system (Ref. 26). The afterburner ECU of the PW TF-30 engine was integrated with the control of the variable-geometry external compression inlet. In late 1970s, NASA Dryden continued its pioneering research in integrated control with the flight test of a cooperative control system, where all functions of inlet control, autopilot, auto-throttle, and navigation systems were combined in a single digital computer on a YF-12 airplane.

In 1981, flight test of the F100 DEEC began at NASA Dryden on the NASA F-15 aircraft. The success of the flight test program allowed the Air Force to elect to put the DEEC into full-scale development and production. The success also stimulated a series of flight research projects in the mid- and late 1980s to study the advanced control modes. These projects, centered on the HIDEC (Highly Integrated Digital Electronic Control modes) program, included: integrated flight and propulsion control, adaptive engine control, extended engine life control, and inlet integration.

In the advanced control research area, the study of the characteristics of compressor surge and rotating stall during this phase enabled the blossoming work in active compressor stability controls of the 1990s. In the late 1970s, theoretical and experimental works on surge and rotating stall were summarized for compressors (Ref. 27). These works prompted NASA to conduct research in surge and rotating stall. A hybrid computer simulation was developed at NASA Lewis to extract the in-stall pumping characteristics of a multi-stage axial flow compressor from engine surge data (Ref. 28).

The advances in multivariable control design and FADEC had stimulated the concept of model-based controls. Since the engine model typically represents the nominal performance of the engine fleet, on-line estimation of model parameters allows the model to be adjusted for each specific engine (i.e., off-nominal performance), even with engine deterioration. This on-line tuning (or adaptive) model is then able to improve both the controlled engine performance and the diagnostic accuracy. In late 1980s, the Kalman filtering approach to adaptive modeling was first applied to jet engines. A piecewise linear, state-variable model of a turbofan engine was adjusted by five estimated parameters, representing five implicit engine component variations (e.g., efficiency and flow variations), using a Kalman filter with in-flight engine measurements (Ref. 29). This work paved the way for the development and flight test of the performance-seeking control (PSC) in the early 1990s (Ref. 30).

5.0 The Integration Phase (1990 to 2002)

5.1 Control System Description

Dual-channel FADECs became the standard control system for jet engines in this phase. Compared to the “first generation” FADECs in the previous phase, they have more built-in test functions; they have some form of embedded engine models to improve engine performance and diagnostics; they have some type of usage and life tracking algorithms; and they are much lighter and smaller per controlled variable due to spectacular improvements in microprocessor speeds and memory technologies.

Electric actuation systems gained wider acceptance. In addition to stepper motors, electro-mechanical actuators have been installed on engines. New sensors, especially diagnostic-specific sensors, are being tested for enhanced engine health management capabilities.

5.2 Control Design Methodology

Subsystem integration for improved overall performance was a driving force for engine control design. Integration of engine control with inlet and exhaust controls, as well as the integration of propulsion and flight controls, made significant advancement in this phase. The issues facing the design of integrated flight and propulsion control systems were analyzed in a NASA-sponsored STOVL (short take-off and vertical landing) controls technology program. A modified F110 engine with ejector-augmentor was assumed as the propulsion system to provide thrust during cruise, and provide lift and reaction (jet) controls during hover and landing (Ref. 31). This work helped the development and piloted simulation of an advanced IFPC design methodology at NASA. The methodology included the H_∞ control synthesis technique, controller partitioning between the airplane and the engine, controller scheduling over a wide operating regime, and nonlinear design techniques such as rate limiting and integrator wind-up protection (Ref. 32).

Much of the modern control design methods described for the Electronic Phase and the Integration Phase was theoretical and experimental, i.e., most of the advanced designs were only validated in simulations or laboratory environment, they were not implemented on real engines. However, the following two examples offer some encouragement for more practical adoption of advanced design methods in the future.

System identification techniques were applied to engine control development in early 1990s. Several operating point models of the Honeywell TFE731-5 engine were identified from ground test and in-flight data. These input-output models were then used as design models to derive the control gain values for the control. After the control laws were implemented in the FADEC, the engine was tested in a test cell. It was found that all the control gains were adequately set. This was the first time that a designed gain value did not have to be adjusted (usually several-fold) in the test cell during control development testing. The engine was then flown with the new control law to 45,000 feet. The altitude-compensated control laws performed exceedingly well, again without the need for adjustment.

After almost 30 years of theoretical development, the multivariable control design methodology was applied to the design of the PW JSF F119 (now designated F135) control law, which was implemented in the engine's FADEC and tested in flight in 2000.

5.3 Modeling and Simulation

Block diagrams have been commonly used to represent control logics and diagnostic procedures. In this phase, GUI-based modeling and simulation tools reached a high level of maturity, and were widely adopted by control engineers to build and analyze engine models. Among all commercial-off-the shelf (COTS) design tools, the MatrixX/SystemBuild and the Matlab/Simulink were most widely adopted.

Automatic software (or code) generation tools became a new standard for real-time simulation and embedded applications. Aside from the auto-code generation tool offered by SystemBuild and Simulink, proprietary tools such as PW's Pictures-to-Code and GE's BEACON were both proven to reduce control and diagnostic software development time significantly. However, the overwhelming cost of maintaining these in-house tools has limited the use of proprietary code-generation tools.

Control system rapid prototyping capabilities were significantly enhanced. Vertically integrated process starting at the top from model-building, control analysis and simulation, automatic generation of control code, code compilation, downloading the code to real-time control hardware (typically a single board computer), and running the control system with the plant, actuator, and sensor hardware in closed-loop has been a standard procedure in a design process to reduce development cost and risk.

5.4 Advanced Control and Flight Research

Flight test of the performance-seeking control (PSC) on the NASA F-15 aircraft started in the late 1980s and finished in the mid-1990s. The PSC took the HIDEC to the next step—onboard real-time adaptive optimization of engine and airplane parameters. A Kalman filter was used to estimate key engine parameters in near-steady state conditions. This program provided valuable information for the self-tuning, onboard engine model that was implemented in the ECU of the F119 engine on the F-22 airplane.

A distortion-tolerant control system was developed and flight-tested in 1997 on the High Stability Engine Control (HISTEC) program (Ref. 33). The control system included a distortion estimation system, which assimilated information from engine face pressure sensors and flight control estimated angle-of-attack and side-slip angle. The estimated distortion level was then used to trim engine actuator commands for stability management.

The propulsion-controlled aircraft (PCA) research represented another contribution in this phase. The PCA used computer-controlled engine thrust to provide a safe landing capability in case of major flight control system failure. Later tests verified PCA operation over the full flight envelope, even in upset conditions with all hydraulic systems turned off, and automatic landing with the ILS (instrument landing system).

The importance of flight test in the validation and verification of control technologies has now been extended to health management technologies. NASA Dryden, with the support of NASA Glenn and NASA Ames, is leading the vehicle health management program to test a number of engine and vehicle health management technologies on an Air Force C-17 airplane with its four PW F117 engines. This program promises to advance the health management capabilities significantly as the flight tests did to engine controls in the past.

Life-extending controls (LEC) were investigated for both large and small engines. NASA pioneered the concept of LEC and demonstrated, in simulation, the objectives of achieving high performance in transient responses and damage mitigation with increased structural durability for rocket engines (Ref. 34). The LEC concept was applied to aircraft turbine engines in mid 1990s. GE, Honeywell, and PW were investigating different methods to reduce damage and increase engine life. One method showed, in a production-quality FADEC-in-the-loop simulation, that thermal-mechanical fatigue and creep/rupture life can be extended significantly by small increases in acceleration transient time and cruise flight time, respectively. The small increase in acceleration time would not violate FAA's (Federal Aviation Administration) engine acceleration time requirement, because the time increase, resulting from reduced fuel flow and turbine temperature, occurred in the final 10 percent of the acceleration (Ref. 35).

Active controls represented new opportunities to improve engine performance, operability, and reliability. Research programs in high-response controls (e.g., hundreds of cycles per second) of surge and stall, tip clearance, and combustion instabilities were sponsored by Air Force, Army, Navy, and NASA. Although the technology readiness levels (TRL) of active control technologies have not reached the implementation stage, they could significantly increase the number of controlled variables and complexity due to their nature of distributed control system.

6.0 Evolution of Controls Complexity

6.1 Number of Controlled Variables

One way to assess the complexity of an engine control system is by the number of controlled variables (Ref. 35). These controlled variables, or actuators, typically include: fuel flow, stator/vane position, valve position, nozzle area, etc. In addition to these multi-valued control variables, there are also discrete, or on/off, control variables, such as engine ignition and anti-ice air. Table 6.1 shows the evolution of engine control variables of the historically important engines (from the control's standpoint). Note that the anti-ice and ignition control variables are not included in the table. Also note that the trend of the number of controlled variables for military fighter engine has outpaced the trend for commercial engines.

TABLE 6.1.—EVOLUTION OF THE NUMBER OF ENGINE CONTROL VARIABLES

Engine model	Year (flt) tested	Number of control variables
GE I-A	1942	1
GE J47	1948	3
GE J79	1954	4
GE TF39	1966	2
GE CF6	1968	3
PW F100	1970	8
AR TFE731	1972	2
GE F101	1972	5
CFM56	1974	2
GE YF120	1989	11
PW F119	1990	8
GE90	1993	3

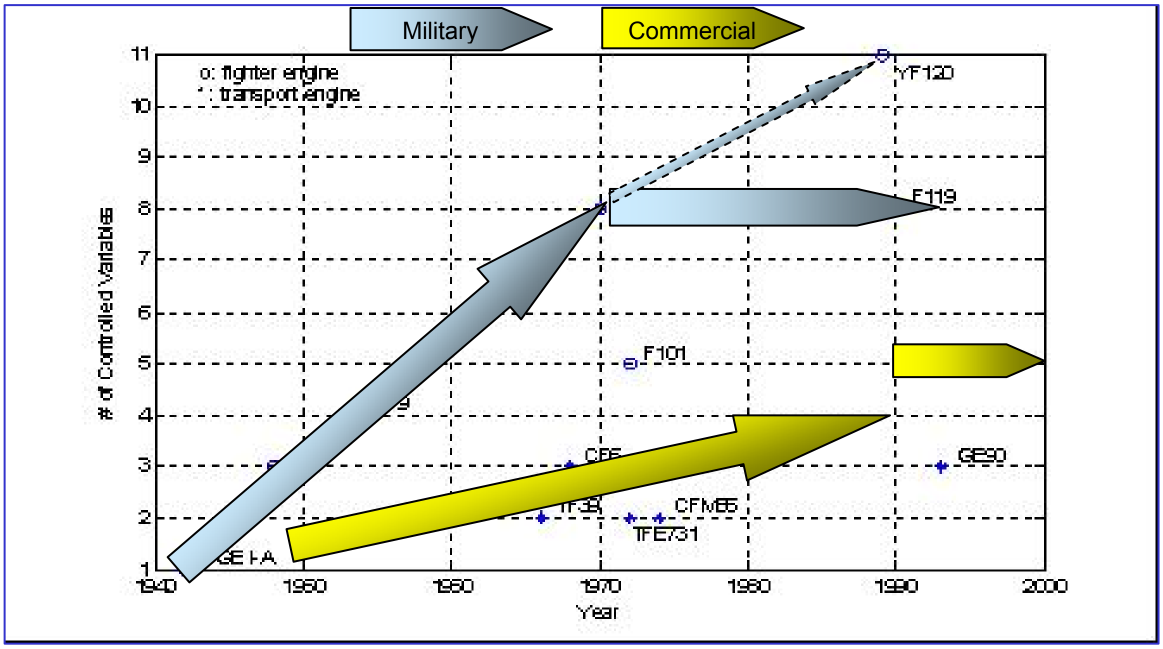

Figure 6.1.—Trends of engine control complexity.

Figure 6.1 graphically depicts the trends for military and commercial engines of control complexity.

6.2 Number of Engine Sensors

In a feedback control system, measurement is made to infer how the physical system under control is doing. Hence, the number of measurements, or sensed variables, is another indication of the complexity of a control system. Table 6.2 shows that the number of engine sensors, not including the power lever position or throttle, has increased with the increasing complexity of the engine controls. The number of sensors is expected to increase rapidly as additional sensors are added in future engines for health management purposes. Figure 6.2 shows the trends in the number of engine sensors.

TABLE 6.2.—EVOLUTION OF THE NUMBER OF ENGINE SENSORS

Engine model	Year (flt) tested	Number of engine sensors
GE I-A	1942	3
GE J47	1948	5
GE J79	1954	5
GE TF39	1966	6
GE CF6	1968	6
PW F100	1970	8
AR TFE731	1972	5
GE F101	1972	7
CFM56	1974	6
GE YF120	1989	11
PW F119	1990	10
GE90	1993	7

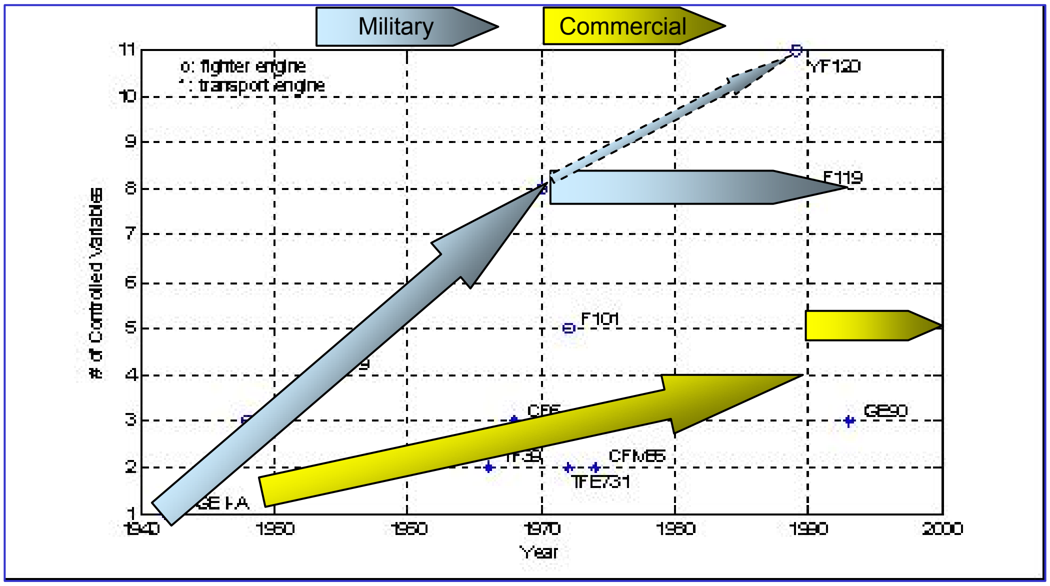

Figure 6.2.—Trends in the number of engine sensors.

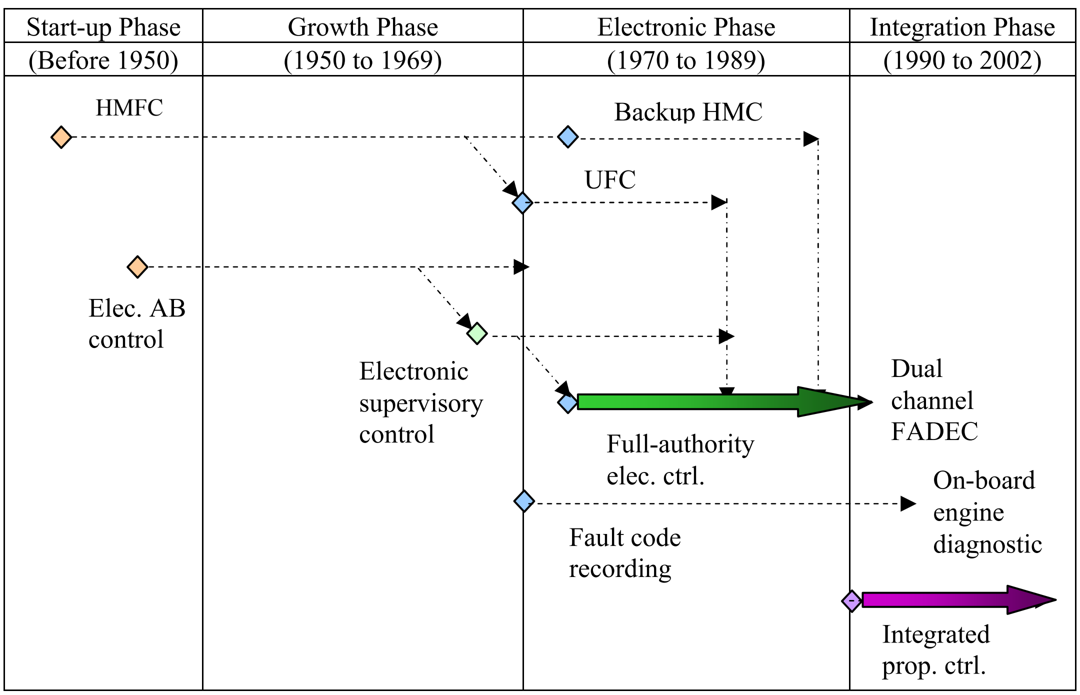

Figure 6.3.—Evolution of engine controls.

6.3 Types of Control Systems

In a control system, the computational unit and algorithms, which “figure out” what values the corresponding controlled variables should be at any operating condition, are called controls. Engine controls have evolved from a simple hydro-mechanical fuel control (HMFC) in 1940s to the full-authority digital electronic control used in all modern gas turbine engines. Figure 6.3 shows the evolution of engine controls of the historically important engines.

7.0 Conclusions

This paper has presented a historical perspective on the development of jet engine control technologies in the U.S. aircraft propulsion industry. The paper focuses on the control technologies developed from 1940 to 2002. The paper also focuses on the control systems of turbojet and turbofan engines, with the belief that these control systems provide a broad representation of the historical development of engine controls in general.

In preparing this paper, we have been challenged with selecting the adequate amount of information from a vast collection of technical papers, books, personal notes, and expert-interview transcripts. We believe that choosing a high-level overview of the technologies that have been implemented on engines, tested in flight (or tested on ground full-scale models), and identifying the technologies that have made significant shifts in paradigms, like the multivariable control, are a good compromise. We may have omitted some technologies that readers think could be included in this paper; we encourage the reader to contact us so that we can continue to update this legacy.

In the process of designing engine control systems, we have taken for granted many common practices like altitude corrections, gain compensation, and limit protections. As we look back at the historical development of these common practices, we begin to recognize their roles in advancing the state-of-the-art of gas turbine engines. We have also gained a deeper appreciation of their contributions to the increased performance, reliability, and safety of jet engines over the last 60 years. We hope this paper can remind us of the dedicated engineers who persevered through difficult challenges. We also hope that the paper can encourage us to continue the honorable tradition of engine controls.

8.0 Appendix—Historically Important Engines

8.1 Start-up Phase

The table is organized by the *engine model*, the *year* when the engine was first flight-tested (or first run on the ground when the flight test date was not confirmed), the *aircraft model*, and the *technology advancements* made by the engine.

TABLE 8.1.—MAJOR MILESTONES FOR PROPULSION CONTROLS IN THE START-UP PHASE (BEFORE 1950)

Year	Engine model	Aircraft model	Technology advancements
1942	GE I-A	Bell XP-59A (1st flt)	Design based on British Whittle engine (single-stage centrifugal compressor with canned combustors) Hydro-mechanical governor. Flame-out protection (min. flow stop). Maximum-flow schedule.
1943	GE TG-100/T31		World's first turboprop engine tested (Ref. 6). First two-spool turbine engine with the free turbine driving the propeller at the front. First axial-flow compressor aircraft gas turbine.
1943	GE I-16	Bell P-59 (1st flt)	First afterburner (AB) experiment on this engine.
1944	GE J-33	Lockheed XP-80 (1st flt)	A direct descendant of the British Whittle engine of the early 1940s. November 1945, the Allison Division of General Motors assumed complete responsibility for the development and production of J33 series engines.
1945	Westinghouse J30	McDonnell FH-1 (1st flt)	The first pure jet fighter for the Navy (Ref. 7).
1946	GE J35	Republic XP-84 (1st flt)	First axial-flow compressor turbojet. Late in 1947, complete responsibility for the production of the engine was transferred to the Allison Division of General Motors.
1948	GE J47	F-86, F-86D (1st flt with AB)	Production started in 1948, the most-produced aircraft turbine engine in history. First electronically controlled afterburner (AB), AB control was linked to main engine control. First anti-ice control system.
1949	PW J52	A-4, A-6	First two-spool, aerodynamically connected turbine engine design.J52-P3 production started in 1959. Predecessor of JT8D.

8.2 Growth Phase

TABLE 8.2.—MAJOR MILESTONES FOR PROPULSION CONTROLS IN THE GROWTH PHASE (1950 TO 1969)

Year	Engine model	Aircraft model	Technology advancements
1951	PW J57	B-50 (1st flt)	First two-spool, aerodynamically connected turbine engine in production. Production started in 1953.
1955	GE J79	NA B-45 (1st flt) XF-4D, F-104	First high compression ratio engine flight-tested. First variable geometry engine, variable-stator compressor. First engine to reach Mach 2 in late 1955.
1956 1959	GE J85	GAM-72 drone T-38	First small turbojet engine. Afterburning version first flown in T-38.
1957	PW JT3	B-707, DC-8	Commercial version of J57 in production. First U.S. commercial turbine engine.
1958	PW J58	SR-71 (1st flt)	First engine to reach Mach 3. Variable intake and nozzle controls. First variable cycle engine (var. comp. bypass). First electronic temperature trim, predecessor of supervisory control. First engine with a controlled bleed valve (during engine start).
1958	GE CJ805	Convair 880 (1st flt) Convair 990	Commercial version of J79. CJ805-23 was the first U.S. turbofan (free turbine driven aft fan); it first flew on the 990.
1958	PW TF30	F-111, F-14	First afterburning *turbofan* engine. Hydro-mechanical fuel control (HMFC) and separate controls for AB and compressor stators.
1959	GE J85/Lift Fan	XV-5A	First lift fan system powered by two J85's tested. Twin lift fans with controllable louvers. First fixed-wing VTOL flight on Republic XV-5A.
1960	GE CJ610	Learjet	Business jet/general aviation version of J85.
1961	PW JT8D	DC-9, B-727, B737	First engine run of commercial version of J52 in 1961. Production started in 1963. Annular full-length bypass duct.
1964	GE J93	NA XB-70 (1st flt)	Predecessor of GE's SST engine, the GE4. 2,300 F turbine inlet temp. with turbine cooling. Mach 3 cruise for a large bomber/transport demonstrated in a 1965 flight.
1966	GE TF39	C-5, B-52	First derivative of the core engine concept from the GE1 demonstrator engine. First GE high bypass ratio (8:1) turbofan. Improved foreign object damage (FOD) rejection.
1968	PW JT9D	B-747 (1st flt)	First PW high bypass ratio (5:1) turbofan.
1968	GE CF6	DC-10	First ground run of the commercial version of TF39 in 1968. Significant increase in fuel efficiency.

8.3 Electronic Phase

TABLE 8.3.—MAJOR MILESTONES FOR PROPULSION CONTROLS IN THE ELECTRONIC PHASE (1970 TO 1989)

Year	Engine model	Aircraft model	Technology advancements
1970	PW F100	F-15	First modular concept engine tested on ground. First unified fuel control (UFC). First supervisory electronic engine control (EEC) - digital. First engine with event history recorder (EHR), predecessor of engine diagnostic unit (EDU).
1972	Garrett TFE731	Falcon, Learjet	First gas turbine engine with full-authority electronic control—analog, single channel. A reduced capability hydro-mechanical control (HMC) as a back up. First modulated inter-stage bleed valve.
1972	GE F101	Rockwell B-1	Hydro-mechanical control (HMC) with full-authority electronic AB control—analog.
1974	CFMI CFM56	DC-8 Series 70, KC-135, B-737	GE F101 core and SNECMA M56 fan, turbine, and gearbox. Better fuel efficiency, lower noise and emissions.
1981	PW F100	F-15, F-16	First flight test of a full-authority digital electronic engine control (DEEC). Single-channel DEEC with a back-up HMC. First FADEC-controlled military engine.
1982	PW JT9D-7R4	B-747-400	Entry into service in 1982. Supervisory electronic control with HMC.
1984	GE F110-100	F-16	Entry into service. Set single-engine reliability and safety record.
1984	PW2037	B-757	First commercial service of advanced turbofan. Dual-channel FADECs. Active tip clearance controls for HPC, HPT, LPT. Multiple bleed valve controls. Engine program plug (EPP) in the FADEC to select multiple engine models. Integrated thermal management for oil and fuel. Advanced thrust reverser. Predecessor of F117 for C-17.
1989	IAE V2500	A320, MD-90	Entry into service. First engine with auto-start (ignition and re-start). Model-based tip clearance control. Central maintenance features built in the FADEC.

8.4 Integration Phase

TABLE 8.4.—MAJOR MILESTONES FOR PROPULSION CONTROLS IN THE INTEGRATION PHASE (1990 TO 2003)

Year	Engine model	Aircraft model	Technology advancements
1990	PW F119	F-22	First flight in 1990. Dual-channel, *active* FADECs. 2-D thrust vectoring nozzle. Self-tuning on-board real-time model (STORM) for diagnostics. Analytical redundancy for gas-path sensors. Separate diagnostic unit (CEDU) from FADEC.
1990	GE YF120		First flight in 1990. Variable cycle engine (variable bypass). Flight-qualified engine that has the highest number of controlled variables.
1992	GE F110-129	F-16, F-14	Entry into service on F-16 in 1992. Full-authority digital electronic control (FADEC).
1992	PW F100-220	F-15, F-16	First life extension control implementation by limiting rotor speed excursions with varying nozzle area and inlet guide vanes.
1995	PW F100-229	F-15 Active	First supersonic-yaw thrust vectoring nozzle flight demonstration (pitch yaw balanced beam nozzle, PYBBN).
2000	PW JSF F119/ F135	JSF	First flight in September 2000. Increased integration of flight-propulsion controls (for short take-off and vertical landing, STOVL). Integrated lift fan and jet propulsion system. First flight-critical propulsion system. First implementation of multivariable control. 3-bearing swivel duct (3BSD) nozzle.
2002	PW 6000	A-318	First flight in January 2002. First commercial application of PW's self-tuning on-board real-time model, STORM.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 2005	Technical Memorandum

4. TITLE AND SUBTITLE

Propulsion Control Technology Development in the United States
A Historical Perspective

5. FUNDING NUMBERS

WBS–22–550–00–01

6. AUTHOR(S)

Link C. Jaw and Sanjay Garg

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–15299

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2005–213978

11. SUPPLEMENTARY NOTES

Link C. Jaw, Scientific Monitoring, Inc., 8777 E. Via De Ventura, Scottsdale, Arizona 85258–3343; and Sanjay Garg, NASA Glenn Research Center. Responsible person, Sanjay Garg, organization code RIC, 216–433–2685.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category: 07

Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

This paper presents a historical perspective of the advancement of control technologies for aircraft gas turbine engines. The paper primarily covers technology advances in the United States in the last 60 years (1940 to approximately 2002). The paper emphasizes the pioneering technologies that have been tested or implemented during this period, assimilating knowledge and experience from industry experts, including personal interviews with both current and retired experts. Since the first United States-built aircraft gas turbine engine was flown in 1942, engine control technology has evolved from a simple hydro-mechanical fuel metering valve to a full-authority digital electronic control system (FADEC) that is common to all modern aircraft propulsion systems. At the same time, control systems have provided engine diagnostic functions. Engine diagnostic capabilities have also evolved from pilot observation of engine gauges to the automated on-board diagnostic system that uses mathematical models to assess engine health and assist in post-flight troubleshooting and maintenance. Using system complexity and capability as a measure, we can break the historical development of control systems down to four phases: (1) the start-up phase (1942 to 1949), (2) the growth phase (1950 to 1969), (3) the electronic phase (1970 to 1989), and (4) the integration phase (1990 to 2002). In each phase, the state-of-the-art control technology is described and the engines that have become historical landmarks, from the control and diagnostic standpoint, are identified. Finally, a historical perspective of engine controls in the last 60 years is presented—in terms of control system complexity, number of sensors, number of lines of software (or embedded code), and other factors.

14. SUBJECT TERMS

Propulsion; Engine control; Control systems design; Adaptive control

15. NUMBER OF PAGES

26

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	