NASA/TM—2005-214019

ARL–TR–3667
AIAA–2005–6905

A Demonstration of a Retrofit Architecture for Intelligent Control and Diagnostics of a Turbofan Engine

Jonathan S. Litt
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

James A. Turso
QSS Group, Inc., Cleveland, Ohio

Neerav Shah
Glenn Research Center, Cleveland, Ohio

T. Shane Sowers
Analex Corporation, Brook Park, Ohio

A. Karl Owen
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

December 2005

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2005-214019

ARL–TR–3667
AIAA–2005–6905

A Demonstration of a Retrofit Architecture for Intelligent Control and Diagnostics of a Turbofan Engine

Jonathan S. Litt
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

James A. Turso
QSS Group, Inc., Cleveland, Ohio

Neerav Shah
Glenn Research Center, Cleveland, Ohio

T. Shane Sowers
Analex Corporation, Brook Park, Ohio

A. Karl Owen
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

Prepared for
Infotech@Aerospace
sponsored by the American Institute of Aeronautics and Astronautics
Arlington, Virginia, September 26–29, 2005

National Aeronautics and
Space Administration

Glenn Research Center

December 2005

Acknowledgments

The authors gratefully acknowledge Sanjay Garg's significant contribution to the development of the overall retrofit architecture, and guidance during the piloted evaluation phase of the project.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

A Demonstration of a Retrofit Architecture for Intelligent Control and Diagnostics of a Turbofan Engine

Jonathan S. Litt
U.S. Army Research Laboratory
Glenn Research Center
Cleveland, Ohio 44135

James A. Turso
QSS Group, Inc.
Cleveland, Ohio 44135

Neerav Shah
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

T. Shane Sowers
Analex Corporation
Brook Park, Ohio 44142

A. Karl Owen
U.S. Army Research Laboratory
Glenn Research Center
Cleveland, Ohio 44135

Abstract

A retrofit architecture for intelligent turbofan engine control and diagnostics that changes the fan speed command to maintain thrust is proposed and its demonstration in a piloted flight simulator is described. The objective of the implementation is to increase the level of autonomy of the propulsion system, thereby reducing pilot workload in the presence of anomalies and engine degradation due to wear. The main functions of the architecture are to diagnose the cause of changes in the engine's operation, warning the pilot if necessary, and to adjust the outer loop control reference signal in response to the changes. This requires that the retrofit control architecture contain the capability to determine the changed relationship between fan speed and thrust, and the intelligence to recognize the cause of the change in order to correct it or warn the pilot. The proposed retrofit architecture is able to determine the fan speed setting through recognition of the degradation level of the engine, and it is able to identify specific faults and warn the pilot. In the flight simulator it was demonstrated that when degradation is introduced into an engine with standard fan speed control, the pilot needs to take corrective action to maintain heading. Utilizing the intelligent retrofit control architecture, the engine thrust is automatically adjusted to its expected value, eliminating yaw without pilot intervention.

Nomenclature

EGT	exhaust gas temperature
FADEC	full authority digital engine control
FOD	foreign object damage
HM	health management
HPC	high pressure compressor
HPT	high pressure turbine
HUD	heads-up display
IWP	integrator windup protection
LPC	low pressure compressor
LPT	low pressure turbine
PI	proportional-integral
PLA	power lever angle

I. Introduction

Turbofan engine performance varies from engine to engine due to manufacturing tolerances, aging, and deterioration caused by use. Generally the control system developed for the engine is robust enough to keep it operating within acceptable boundaries for several thousand flight cycles. A typical inner-loop control architecture uses fuel flow to control fan speed, which is assumed to be highly correlated to engine thrust, the unmeasured variable of interest. However, as the engine ages, the relationship between fan speed and thrust changes. If all engines on a multi-engine aircraft do not have the same throttle-to-thrust relationship, a thrust imbalance results, producing unwanted yaw, which requires pilot intervention to correct. If thrust were directly controlled, this situation could be avoided. It is possible to achieve the same result using fan speed control by adjusting the fan speed reference signal to accommodate the degraded throttle-to-thrust relationship.

The adjustment of fan speed command implies the use of an outer loop control. Knowing how much to adjust it, and more importantly why it needs to be adjusted, implies intelligence. An Intelligent Propulsion Control architecture is an architecture that increases the level of autonomy of the engine. In this context it means that it should at least be able to recognize performance deterioration, diagnose faults, and alter its power setting to recover whatever lost thrust is possible within the physical constraints of the system, even with degraded capability (ref. 1). Thus an instantiation of such an architecture should be populated with at least some basic diagnostic/health management functions along with some model-based reasoning ability about the engines' degraded performance and operability.

The remaining portions of this section give an overview of pertinent aspects of the turbine engine industry interleaved with descriptions of enhancements that would enable the implementation of an Intelligent Propulsion Control architecture, given the current status of that industry. This is followed by a description of the proposed architecture in general, plus details of the current implementation. Several examples demonstrating various degradation/fault scenarios are presented next. Finally, conclusions are drawn about the effectiveness of the implementation of the Intelligent Control architecture.

A. Turbofan Engine Operation and Degradation

A commercial turbofan engine gas path consists of both rotating and non-rotating components arranged from inlet to exhaust. The first rotating component of a turbofan engine is the fan, which is behind the engine inlet, and in a commercial engine provides most of the thrust by accelerating a vast quantity of air in the front of the engine and exhausting it directly out the back, bypassing the other components. The first of these remaining components is the booster, also known as the low pressure compressor (LPC), which is followed by the high pressure compressor (HPC). This opens into the combustor where fuel is injected and burned. The resulting hot gas drives the high pressure turbine (HPT) and the low pressure turbine (LPT), which power the fan and compressors. Each of these components affects the engine's performance, and the performance degradation is embodied in component health. The state of each component's health involves characteristics that degrade over time: such features as efficiency, flow capacity, and seal leakage. These tend to change slowly over many flights, but may change abruptly with the occurrence of a sudden fault. A change of as little as several percent to efficiency and flow capacity may represent the full permissible degradation of the component.

B. Trim Adjustments and Automatic Controls

Asymmetric thrust during flight has a complex, usually unwanted, effect on both the aircraft attitude and direction of flight. This imbalance will initially cause the aircraft to yaw, i.e., the direction of flight will be slightly different than the line through the front-to-back axis of the aircraft. This has several consequences. First, the difference in the airflow over the upwind and downwind wings will cause the upwind wing to generate more lift and rise, causing the aircraft to bank. The yaw will also increase drag, causing the aircraft to slow and, if not corrected, begin a gentle descent. Finally, even if the tendency to bank is counteracted, the differential thrust will cause the aircraft to slowly change its direction of flight. There are several approaches to addressing this problem, some manual and some automatic. When operating in a manual mode, the pilot will first need to determine the cause of the unexpected yaw. His actions may include, for example, asking the following three questions:

1. Are both sides of the airplane the same, symmetrical (e.g., are there bombs on one side only)?
2. Is rudder trim 0 degrees?
3. Are engines at the same operating condition (rpm, fuel flow, EGT)?

To return to straight and level flight, the pilot will normally first reduce the aircraft yaw to zero by use of rudder trim (an incremental offset of the control surface for trimming the plane in flight) or rudder. Alternatively, the pilot may adjust each throttle independently to balance the thrust while maintaining airspeed. Then he/she will return the aircraft wings to level attitude using aileron and either adjusting power to return to the original airspeed or adjusting pitch to maintain level flight at the new airspeed. Normally, all of these control inputs are accomplished more or less simultaneously. The drawback to either adjusting trim or using differential power is that each approach is only valid at one power setting and airspeed and therefore must be adjusted for changes in flight operating conditions. In cases where power is adjusted often within a relatively short period of time (the approach to landing, for example), the pilot will likely use rudder input for compensation rather than rudder trim, increasing the workload.

There are automatic methods available that can perform a similar task, depending on the airplane, without necessarily determining the root cause of the yaw. These autopilot features are designed to relieve pilot workload by performing the basic piloting functions. Various autopilot modes are built into the aircraft's automatic flight control system (ref. 2). They control the longitudinal and lateral-directional modes, including pitch attitude hold, altitude hold, speed or Mach hold, bank angle hold, and heading hold. These modes achieve their goal by manipulating the flight control surfaces. However, a low-speed hold mode called auto-throttle manipulates the throttles to maintain velocity; it is used on approach for glide slope intercept. A combination of the preceding autopilot modes would generally be able to overcome thrust imbalance-induced yaw. An integrated flight/propulsion approach to compensate thrust imbalance is the Thrust Asymmetry Compensation system (ref. 3) that adjusts rudder to balance the estimated thrust differential; this is still part of the flight control system, however.

It makes no difference whether thrust asymmetry is counteracted by thrust compensation, flight surface trim, or a combination, as long as the underlying cause is understood. The main concern is that without a higher level of intelligence, the flight control system is merely reacting to a disturbance, and that if the yaw is the result of an engine problem that the pilot should be aware of, the autopilot is masking it (ref. 4). This is especially important because autopilots have been known to cause confusion that results in pilot error even when nothing is wrong (refs. 5 and 6). It is a philosophical question as to where the intelligence should reside, and it is accepted that the propulsion system is subordinate to the flight control system, but it must also be recognized that the propulsion system is extremely complicated with its own complex control system, while to the flight control it is merely another actuator. Thus it stands to reason that as intelligence increases at both the flight and propulsion levels, in the hierarchical structure of an Intelligent Control system, information about the engines going to the flight control should be basic and simple: engine diagnostics should be performed at the propulsion control level.

C. Engine Diagnostics

Turbine engine diagnostics is critically important to safe operation of the aircraft. Although engines are highly reliable, certain faults have the potential to disrupt the vehicle's operation catastrophically. Engines can fail in multiple ways, and the ability to detect and isolate the fault should be the first step to accommodation, or remedial action by the flight control. A significant challenge for propulsion system diagnostic algorithms is that component faults, and actuator and sensor faults or biases tend to manifest themselves in similar ways (refs. 7 and 8), and there are too few sensors on an engine to allow positive identification of an anomaly. Diagnostic algorithms that can differentiate between the various fault types (refs. 9 and 10) should always be part of an Intelligent Propulsion Control architecture because diagnostic systems that can isolate a fault as well as estimate its magnitude may enable the continued safe operation of the aircraft temporarily, and potentially prevent in-flight shutdowns of an engine, or even the loss of a vehicle (ref. 11).

D. Propulsion Control

The development of control laws for a turbine engine is an involved process. Typical aircraft engine control systems maintain fan speed or engine pressure ratio to regulate thrust, which is not directly measurable. The controllers are generally based on a variant of a Proportional-Integral (PI) scheme, combined with limit logic (fig. 1). This limit logic consists of a series of *min select* and *max select* blocks, each of which selects a fuel flow rate command based on various physical limits, acceleration/deceleration schedules (reference signal for rotor speed rate-of-change vs. rotor speed), and the current operating state (speed governor loops). The final command that exits the selection logic block is integrated to produce a new total fuel flow. Thus an increment of zero will result in no change in fuel flow, and a constant steady fuel flow will occur when steady state error is eliminated.

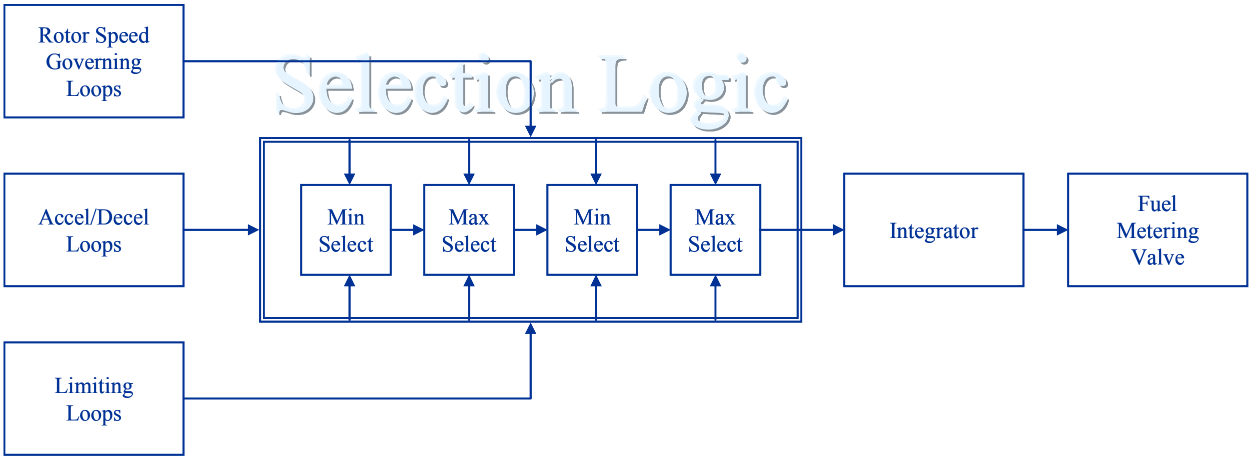

Figure 1.—Typical turbine engine control logic.

The limit logic is quite complex to develop and validate, and extensive simulation testing is required before it is ready to be implemented. The logic might be developed in a block diagram language format that can be compiled into executable code that runs on a flight-certified Full Authority Digital Engine Control (FADEC). The FADEC software implementation must go through a rigorous verification and validation process to meet stringent Federal requirements (ref. 12). The time and cost involved in developing and certifying an engine controller make it prohibitive to perform significant modifications to existing FADEC code.

E. Retrofit Architectures

A retrofit control architecture is one that can be added on top of an existing structure without significant modification. It should alter the signals into or out of the existing controller, but the controller itself should remain intact. For a complex system that requires certification, it might be easier to add externally than to start from scratch, so that, if anything, only the new portion needs additional certification. Several retrofit architectures have been proposed for reconfigurable or adaptive flight control (refs. 13 to 16) and propulsion control (refs. 17 and 18). The development of an Intelligent Control structure for the propulsion system of an airplane is desirable because of safety and operability concerns, but because of the complexity of the FADEC, it is an excellent candidate to be implemented as a retrofit.

II. Intelligent Retrofit Architecture

The proposed retrofit architecture is shown in figure 2. The purpose of the architecture is to automatically maintain balanced thrust as the engines deteriorate with use. The system works by adjusting the fan speed setpoint of each engine individually so that its net thrust is the same as for a new engine for the demanded PLA, within the physical constraints of the system. The architecture is hierarchical with the lowest level performing standard engine control, the next level up maintains balanced thrust with an outer loop thrust control, and the top level consists of the health management and intelligent thrust demand logic. This whole structure is below the flight/mission level. The role of the mission level controller (or intelligent flight controller) is to carry out a mission determined by the capabilities of the overall system (engines and airframe) and modify it based on new information about the situation and the health of the system. For instance, if the engine is unable to meet the demand in a safe way, this information is reported to the intelligent flight controller or mission manager and the set point is adjusted by logic to maintain balanced thrust at a safe level. The mission manager will not be considered in this implementation. Figure 2 shows the overall architecture in block diagram form. The blocks in yellow represent the engines under standard closed loop fan speed control. Above each of the yellow blocks hierarchically is a thrust estimator which generates an estimate of the thrust the engine is producing for use with the outer loop thrust control (green boxes). The blocks along the top in the salmon box represent the structure of an intelligent control framework. They consist of the PLA to output (thrust, etc.) mapping, the Health Management (HM) block, and the thrust setpoint logic for the outer loop control. The HM block determines the fitness of the engine to carry out the expected mission, and finds a way to achieve it if possible, through the thrust setpoint logic. Otherwise it coordinates with the Mission Manager to modify the requirements on the engine to an acceptable level.

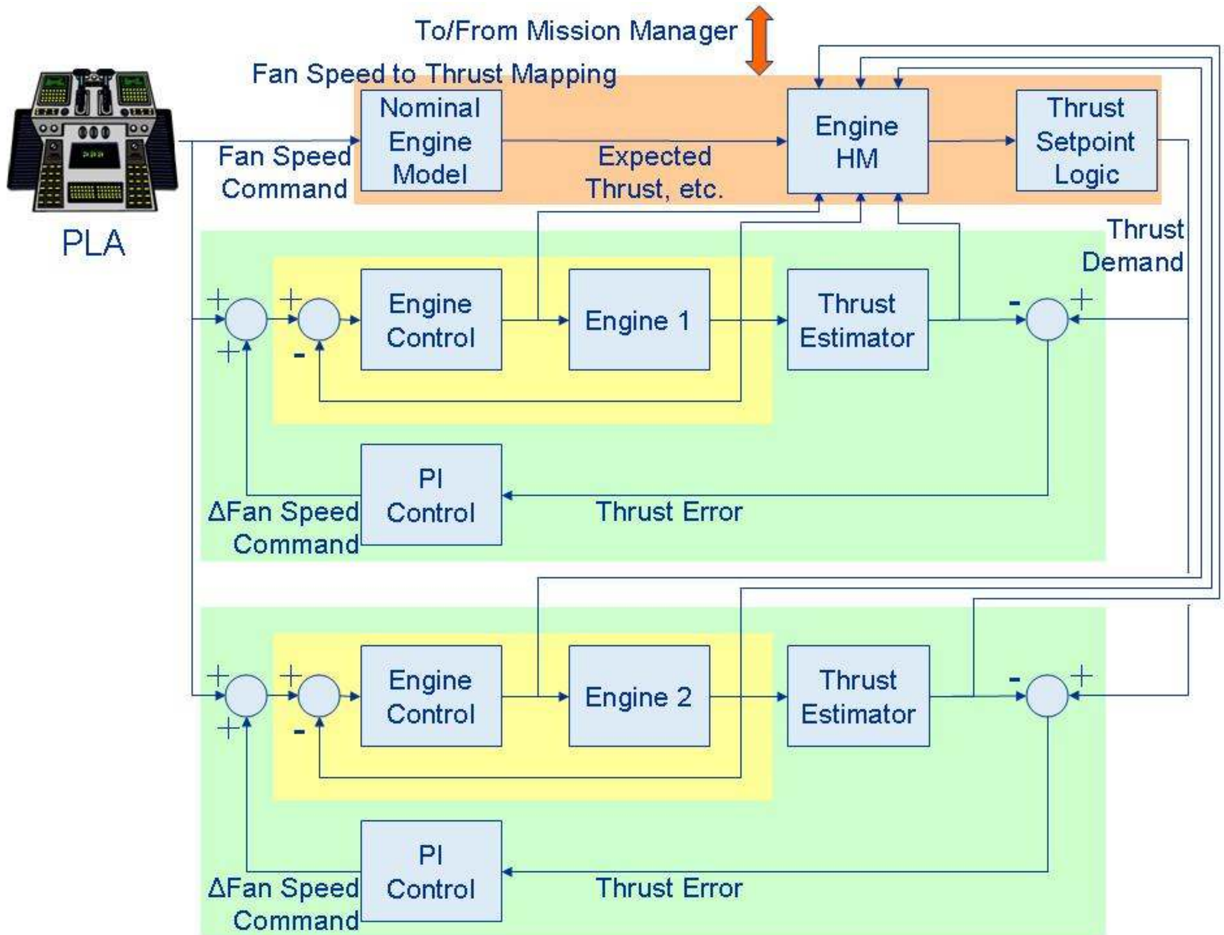

Figure 2.—Intelligent retrofit architecture. The hierarchical structure consists of the Inner Loop or Direct Control (in the yellow boxes), the Outer Loop Control (in the green boxes), and the Intelligent Control (in the salmon box).

A. Direct Control Level

The Direct Control Level (yellow box in fig. 2) contains the standard engine controller. It is usually a Full Authority Digital Engine Controller (FADEC) which is designed to maintain fan speed for performance while not exceeding operability limits. It consists of an incremental Proportional-Integral (PI) controller for steady state fan speed control, as well as acceleration and deceleration schedules and other limit logic. In the current implementation, the fan speed control is designed using the Edmunds or KQ technique (refs. 19 and 20), a design methodology that selects the controller gains such that the closed loop system matches a target transfer function. When the same target transfer function is used to design controllers throughout the flight envelope, the engine response to throttle commands is similar at multiple operating points. This has the advantage that the pilot can expect consistent performance across the flight trajectory.

B. Outer Loop Control

The Outer Loop Control (green box in fig. 2) adjusts the reference signal for the Direct Control. In general, the Power Lever Angle (PLA), which is a pilot input, sets the fan speed command that is calibrated to achieve a desired thrust. However, with engine degradation or some other change in the throttle-to-thrust relationship, the PLA setting will not produce the desired thrust. In order to bring the thrust to the correct level, the fan speed command is adjusted by the outer loop controller. The FADEC logic is designed to prevent the engine from operating in an unsafe mode, so the incremental fan speed command, which enters the FADEC along with PLA, will not drive the engine into an inappropriate operational regime. The change in fan speed command is obtained by driving the error in thrust to zero. Since thrust is not measurable in flight, it must be estimated. The thrust estimator implemented here uses a Kalman filter with an optimal reduced order model of the effect of engine degradation (ref. 21), which has an error of generally well under 1 percent of the total net thrust. The inputs to the Kalman filter are corrected fuel flow and the seven corrected sensed engine variables. The use of corrected variables as inputs to the linear estimator extends its range because the correction factors have the effect of transforming the engine operating condition to a standard operating point (ref. 22), the design point in this case. This allows meaningful comparison of engine data at different conditions and also different levels of degradation (ref. 23). In a practical sense, it enables the Kalman filter to accurately estimate the thrust of a degraded engine at an operating point far from the point where the optimal linear estimator was designed. The difference between the estimated and desired thrust is fed through a PI controller which adjusts the fan speed command until the thrust error is zero. The outer loop controller is tuned to maintain thrust without oscillation or overshoot. The closed outer loop system is assumed to be stable throughout the flight envelope because the inner loop transfer function is constant due to the use of the KQ control design methodology, even though the engine itself behaves nonlinearly.

C. Intelligent Control

The Intelligent Control Level (salmon box in fig. 2) contains the parts of the control structure that evaluate the safety, performance, and capabilities of the engines. Unlike the lower levels for which each engine had a copy, there is only a single copy of this level; it monitors the propulsion system of the aircraft. It takes input from both engines (control signals, sensed variables, thrust estimate, etc.) to determine each engine's current health and fitness for the mission. It also generates the outer loop thrust command that both engines follow. In this implementation, the outer loop thrust command is a Kalman filter-based estimate of the thrust of a nominal engine at the current operating condition. The reasoning behind the use of the nominal engine model's thrust estimate as the command is that it should minimize the impact of estimation error since the estimators are identical. The Outer Loop Control level is shown without integrator windup protection (IWP) on the PI controller because the Intelligent Control should be able to determine if a thrust command is appropriate based on the condition of the engine and knowledge of its operational limits. In practice, IWP and even an on/off switch for the incremental fan speed command would probably be implemented as a safety precaution. Ideally, activity at the Intelligent Control Level will be limited to assessment and consent, but as the engines age and degrade, or when an anomaly occurs, the health management algorithms determine the appropriate action, which generally has to do with the fan speed setting. If the Intelligent Control determines that the condition of an engine is such that corrective action is beyond the scope of the propulsion control (for instance, a problem that might compromise the mission) it communicates this information to the Mission Manager. What the Intelligent Control does not do is adapt the inner loop control; since this is a retrofit architecture it is specifically designed to adjust the signal going into the FADEC, not the FADEC itself. It is clear that there is nothing about the architecture that fundamentally prevents it from adapting the inner loop control if desired; the implementation would only require an extra connection directly to the Engine Control block (ref. 24).

III. Examples

The demonstration vehicle is a modified large transport aircraft with two, wing-mounted commercial-type high bypass engines. The airframe and engine models are full envelope, nonlinear, high fidelity simulations that were interfaced to produce a realistic integrated system that can be flown in a flight simulator. The original airframe had four mid-sized engines, which are replaced by two large, high power engines for these examples. The two engines are widely spaced to exacerbate the thrust imbalance-induced yaw. Each engine uses the hierarchical intelligent control architecture shown in figure 2, with the inner-loop engine control maintaining fan speed.

The flight simulator was developed for preliminary piloted evaluation of control designs. It has a fixed-base, rudimentary cockpit with four pilot inputs: throttle, pitch stick, lateral stick, and rudder pedals (fig. 3). In the limited simulator setup, the single throttle sets the fan speed command for both engines; the pilot cannot demand power from each engine individually. Two inputs can be generated through stick movement: pitch stick by forward and back movement, lateral stick by side to side movement. The final pilot input comes from the rudder pedals. There are no trim inputs and no autopilot modes available. Thus the pilot is forced to counter any thrust imbalance by manually adjusting and holding the vehicle's control surfaces. This makes the task somewhat more complicated than when trim and autopilot are available, but the objective here is to demonstrate an alternative that specifically addresses propulsion system issues without obscuring the problem by using a flight control solution.

Three scenarios were run to evaluate the system's performance in real time, two steady state and one transient; only the transient scenario was piloted. The scenarios were limited to cases where fan speed adjustment is all that is required. All scenarios started at the same initial operating point (defined by altitude, Mach number, and throttle position), where the plane is basically trimmed resulting in essentially straight and level flight. In each case, the

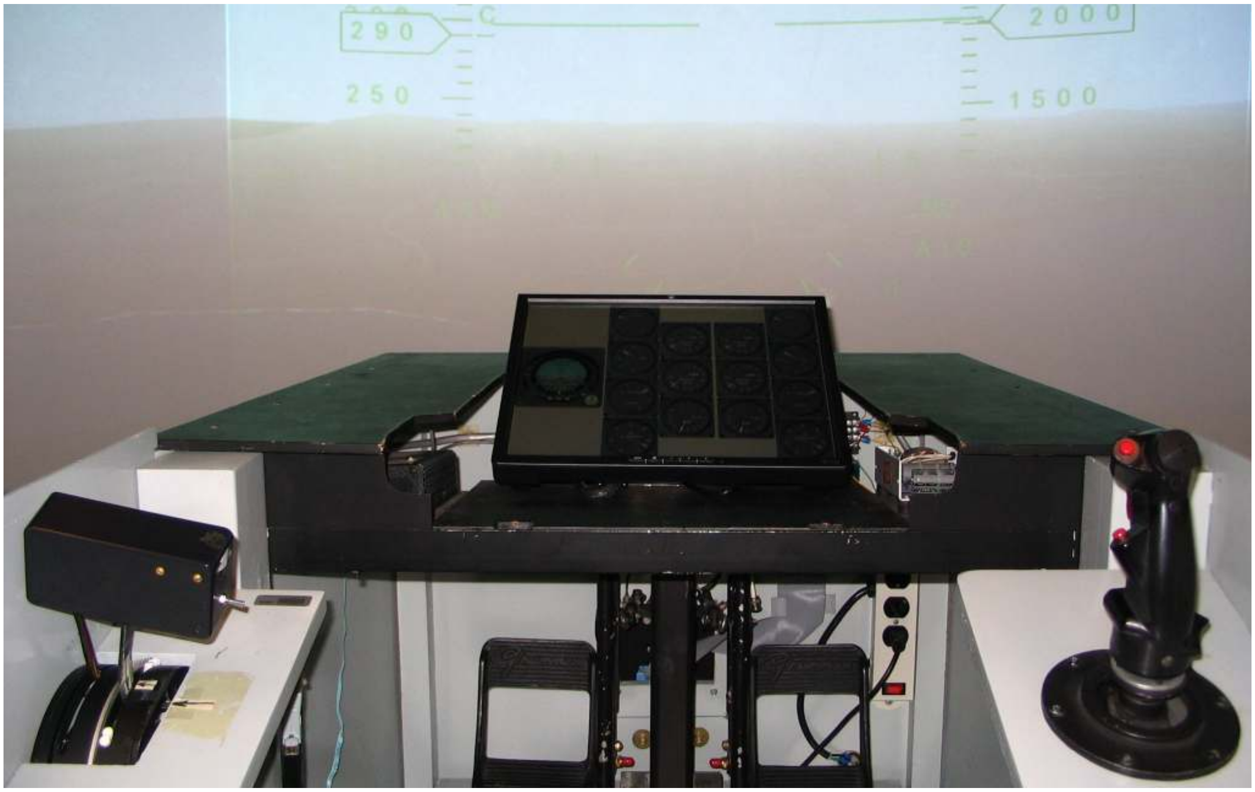

Figure 3.—The flight simulator used to evaluate the Intelligent Control architecture.

simulation ran with both engines nominal for the first 10 seconds, then a linearly increasing degradation was introduced into the left engine over a span of 90 seconds. The intent was for the degradation to enter slowly enough that the engine would not go through a significant transient, mimicking true aging behavior, but quickly enough that the system's response to a fault could be evaluated. Three cases were run for each scenario: 1) baseline, both engines nominal, 2) one engine degraded, outer loop control off, and 3) one engine degraded, outer loop control on.

A. Degradation to Front of Engine

In this unpiloted example, the fan and compressors were degraded, perhaps indicating micro-FOD (foreign object damage) or erosion due to particle ingestion (ref. 25). Particular flight variables of interest for the nominal case and for the degradation scenario with the intelligent hierarchical outer loop control off and with the intelligent hierarchical outer loop control on are shown in figure 4. The corresponding normalized engine variables are shown in figure 5. When the left engine is degraded, the plane rolls and pitches slightly and starts to turn slowly but noticeably to the left without pilot intervention. Additionally, Mach number drops and altitude decreases. These adverse responses are all eliminated when outer loop control is on. The engine variables without outer loop control illustrate that the thrust estimate tracks thrust well and fan speed is maintained. With the intelligent hierarchical outer loop control turned on, the fan speed command is adjusted in the degraded engine to bring the thrust to the desired level. This keeps the plane flying straight as if both engines were nominal. In this case the Mach number and altitude are close to their steady state values, and heading remains constant. EGT is slightly higher than with outer loop control off. In all three cases, the thrust estimate is close enough to the true value that it is hard to distinguish between them in figure 5. The largest difference is in the degraded case with outer loop control off as the engine operating point moves away from the estimator design point.

Figure 6 shows the instrumentation display of the airplane with the left engine degraded, outer loop control off. Fan speed is the same for both engines, but fuel flow, EGT, and core speed are all higher for the degraded engine.

Figure 7 shows the out-the-window view and Heads-up display (HUD) for the same case as the shown in figure 6. The heading (which started at 270º) and roll deviations are obvious.

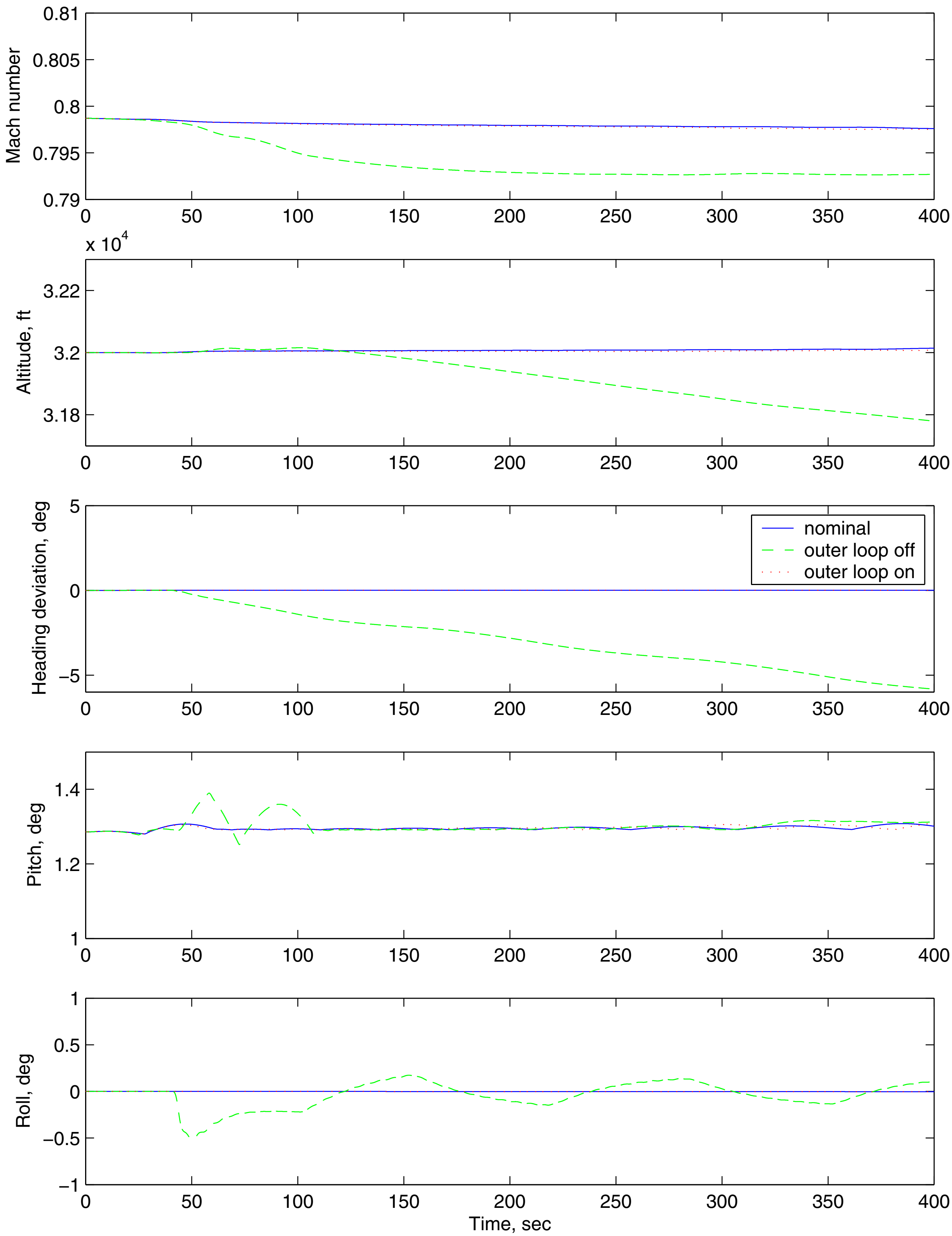

Figure 4.—Selected flight variables for the case with degradation in the front part of the engine.

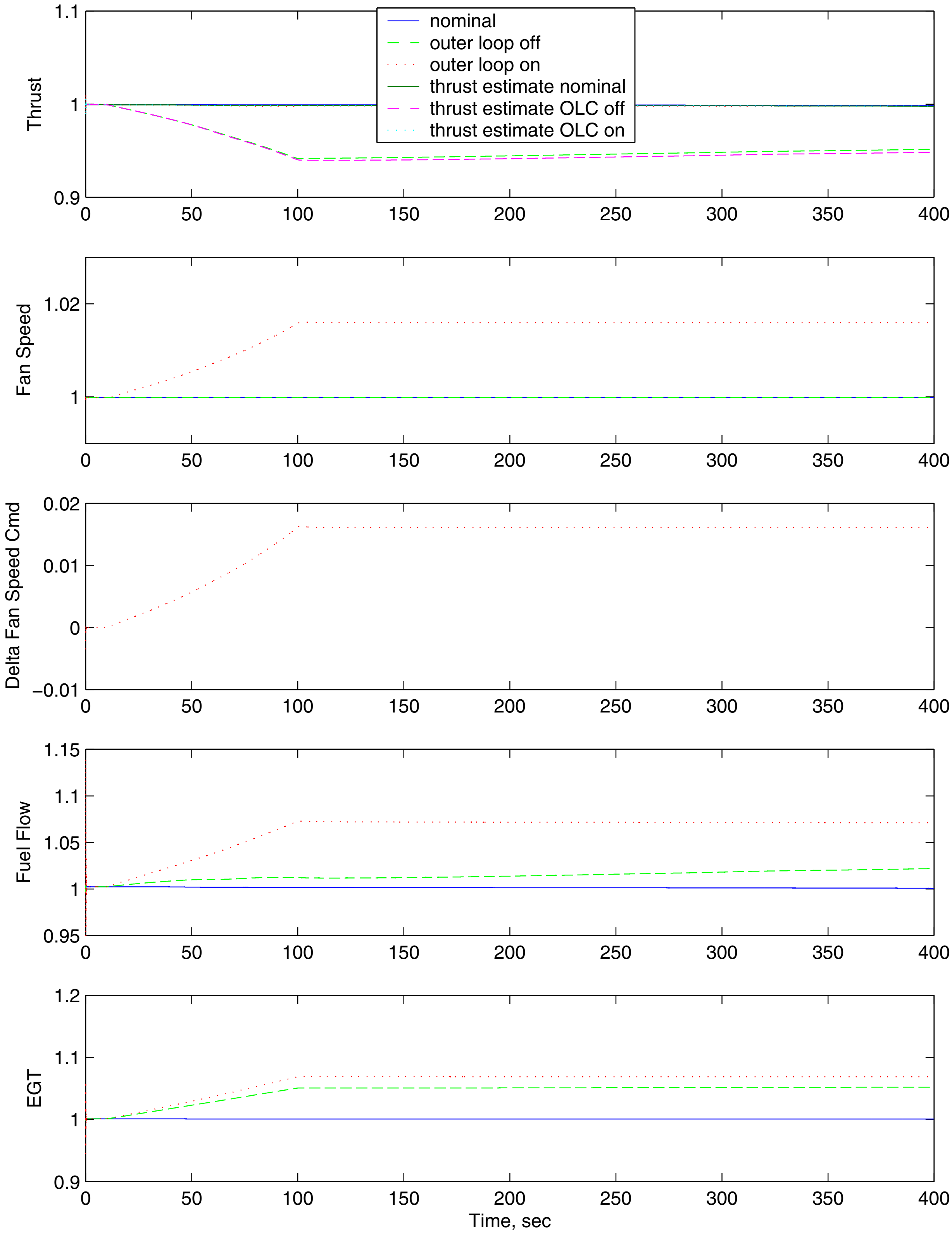

Figure 5.—Selected normalized engine variables for the case with degradation in the front part of the engine. OLC stands for outer loop control in the legend.

Figure 6.—Heads down instrumentation display showing variables for the two engines.

B. Degradation to Engine Hot Section

In this unpiloted example, the turbines were degraded, which is a symptom of having flown through volcanic ash (ref. 26). This type of degradation has the opposite effect of the previous case. In this case thrust increases along with fuel flow and EGT. Thus the altitude and Mach number increased and the plane turned to the right once the turbines were degraded. Particular flight variables of interest for the nominal case and for the degradation scenario with the intelligent hierarchical outer loop control off and with the intelligent hierarchical outer loop control on are shown in figure 8. The corresponding normalized engine variables are shown in figure 9. The thrust estimate converged slightly more slowly than in the previous example, but settled very close to the true value. Again, with outer loop control on, the airframe responses matched those for the nominal case. The fuel flow and EGT both decreased with outer loop control on, providing the double benefit of fuel savings and component life savings as compared to the case where outer loop control is off. This is an important result because in engines with fan speed control, thrust tends to increase with overall degradation (ref. 27).

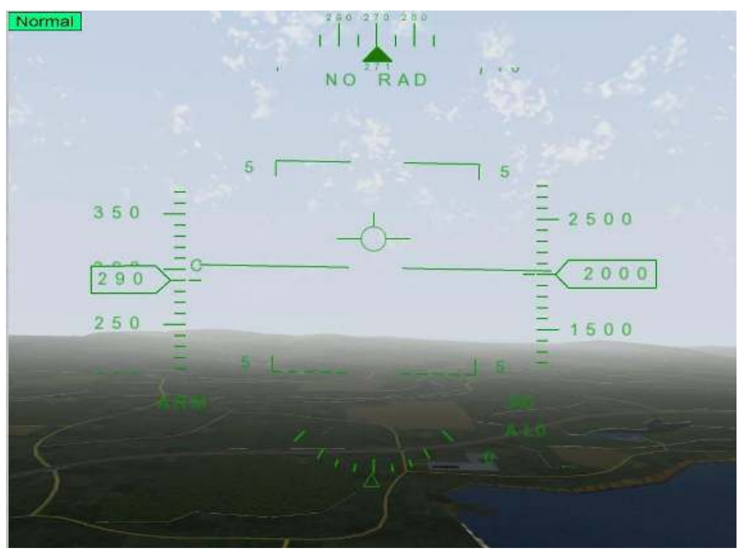

Figure 7.—Cockpit view with heads up display.

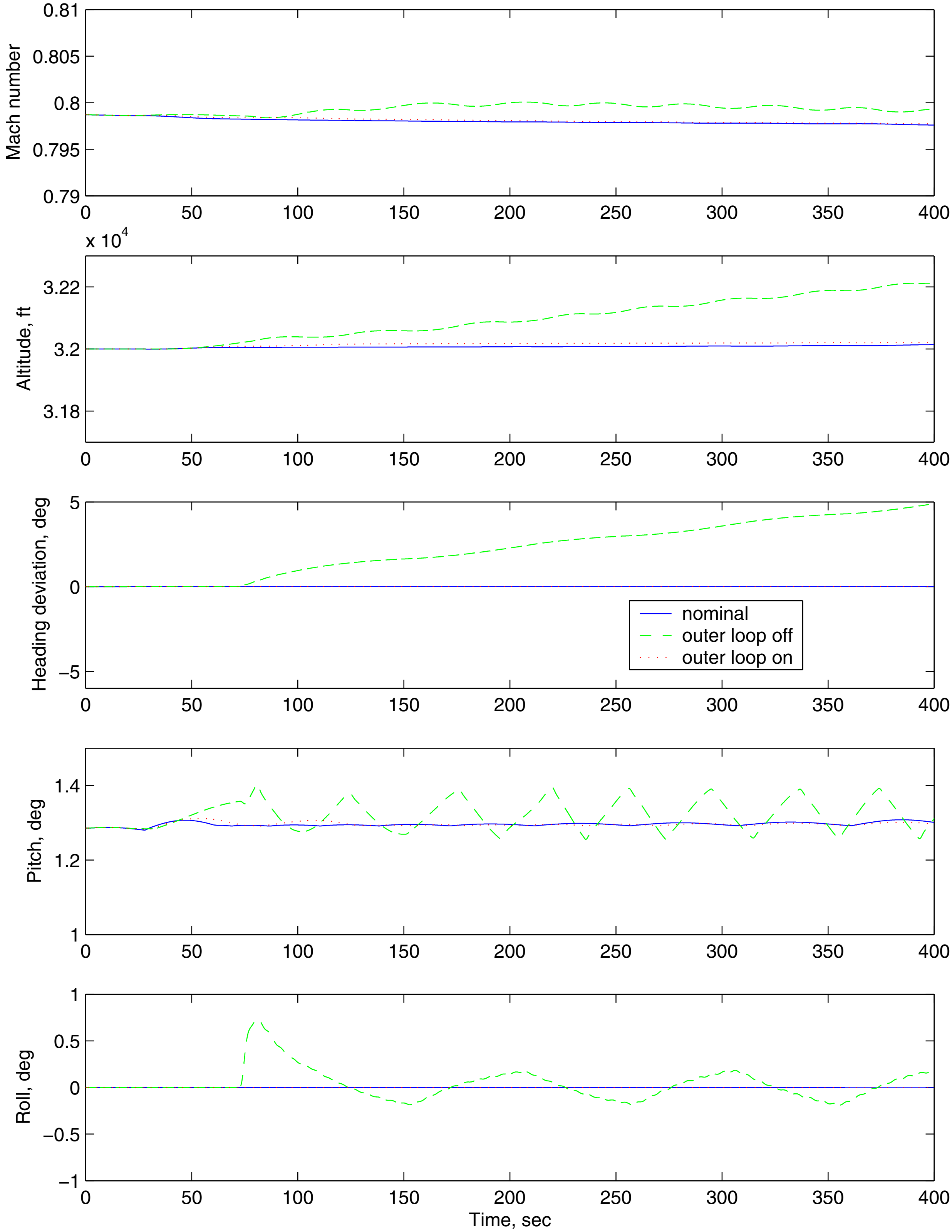

Figure 8.—Selected flight variables for the case with degradation in the hot section of the engine.

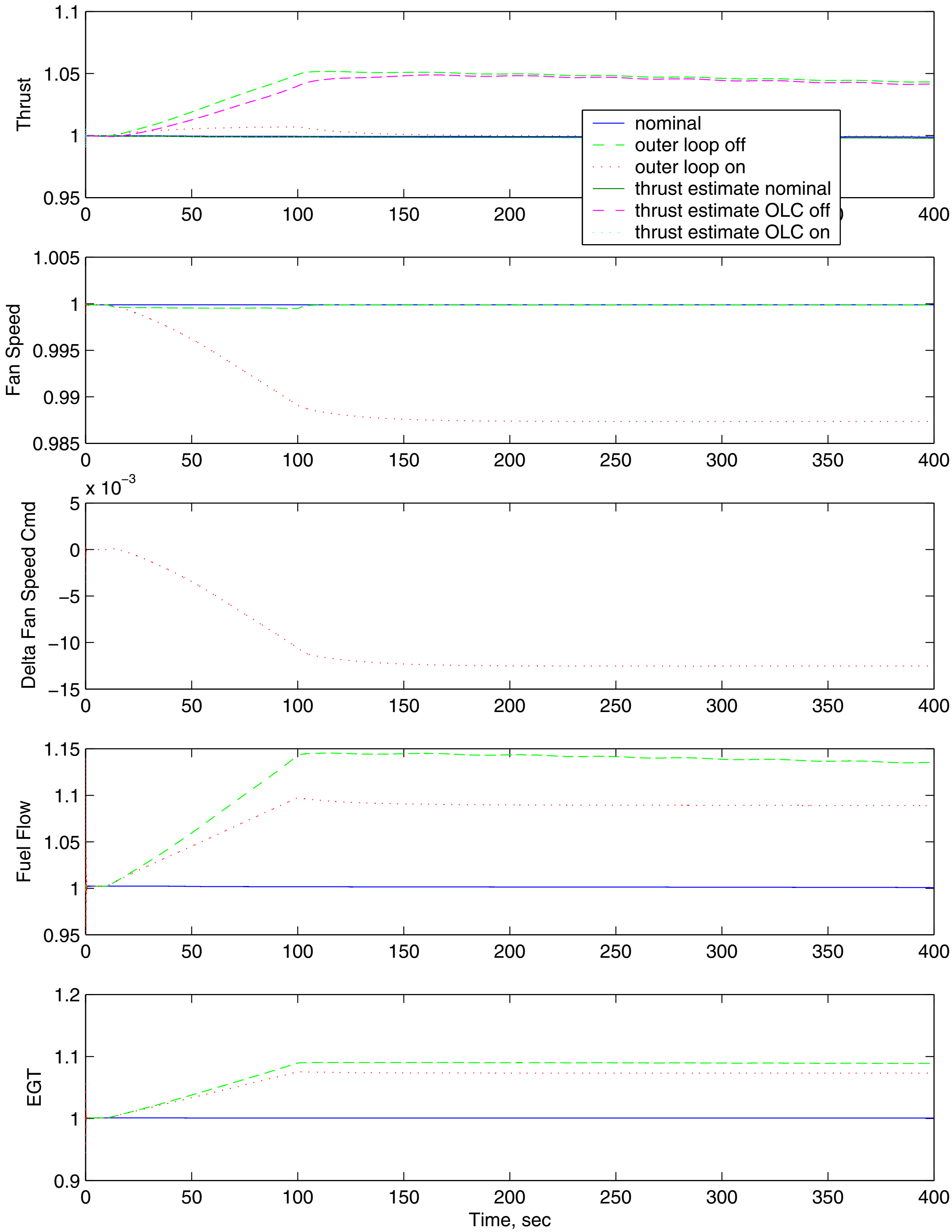

Figure 9.—Selected normalized engine variables for the case with degradation in the hot section of the engine. OLC stands for outer loop control in the legend.

C. Transient Flight

In this example, a pilot flew the simulator over a defined five-segment profile given in table 1. Throughout the flight he attempted to maintain heading and indicated airspeed.

TABLE 1.—FLIGHT PROFILE FOR EXAMPLE.

Segment	1	2	3	4	5
Fan Speed	86%	90%	88%	82%	86%
Indicated Airspeed	290 knots	290 knots	290 knots	290 knots	290 knots
Heading	270º	270º	270º	270º	270º
Altitude	32,000 feet	Climb	33,000 feet	descend	32,000 feet
Duration	3 minutes	-	3 minutes	-	3 minutes

The pilot flew three cases: both engines nominal, one engine degraded with outer loop control off, and one engine degraded with outer loop control on. As before, the fan and compressors were degraded over 90 seconds beginning after 10 seconds. This type of degradation reduces thrust for a given fan speed. The pilot had not practiced much in the simulator and did not know the type of degradation nor when nor how it was injected. Particular flight variables of interest for the nominal case and for the degradation scenario with the intelligent hierarchical outer loop control off and with the intelligent hierarchical outer loop control on are shown in figure 10. The corresponding normalized engine variables are shown in figure 11. Figure 10 illustrates that the pilot was able to fly the plane approximately equally well in all three cases, however there was more variation in roll in the degraded case with outer loop control off. The pilot inputs in figure 12 indicate that the effort required by the pilot to fly the profile was about the same for the nominal case and the degraded case with outer loop control on. In the degraded case with outer loop control off, however, the pilot moved the stick side to side and used the rudder pedals constantly, indicating a considerable increase in workload. The pilot confirmed that with outer loop control on, the workload was significantly less and said he did not have to worry about heading. In the degraded case with outer loop control off, the pilot said the plane was hard to fly but he could not say why; he said it was much easier to fly with outer loop control on. He anticipated that if he had rudder trim available (the flight simulator does not have that feature) the difference between cases would not have been as significant. The pilot did say that the disparity between the engines (speeds and EGT) with outer loop control on is noticeable, and he would be uneasy about that if he did not know that the outer loop control was causing it, i.e., it would need to be mentioned in the flight manual.

D. Discussion

In the first two straight and level flight examples no pilot was present but the deviation from steady state implies that pilot intervention is required to maintain trim. The first and last segments of the profile in the final example correspond to the first example, demonstrating what is actually involved for the pilot to maintain heading and airspeed. The third example showed a clear and obvious difference in the amount of effort required to maintain flight path with outer loop control on, which was confirmed by the pilot. Thus the examples demonstrate that in each case, with outer loop control on pilot workload is reduced, even if the additional workload consists of adjusting rudder trim, as for straight and level flight. In all of these examples, an autopilot could probably have maintained heading and airspeed, but it could also mask any real problem with the engine that the pilot should be aware of. The significant benefit of the Intelligent Hierarchical Control architecture, which is not explicitly illustrated in these examples, is that an engine anomaly, which is the cause of the performance change, can be detected and isolated, as well as being merely accommodated as an autopilot does.

A problem encountered with the relatively fast injection of degradation, which resulted in a sudden yawing moment, is the onset of Dutch roll: churning oscillations in yaw and pitch. This was mitigated somewhat by ramping in the degradation over 90 seconds. Dutch roll is a common phenomenon that should be handled by an autopilot mode; it is not a shortcoming of the Intelligent Control architecture implementation.

The process of degradation is gradual and in general the outer loop compensation will not be noticeable. Because in the examples the degradation was injected fairly rapidly, almost like an abrupt fault, it demonstrates that the architecture is general enough to accommodate faults as well as degradation.

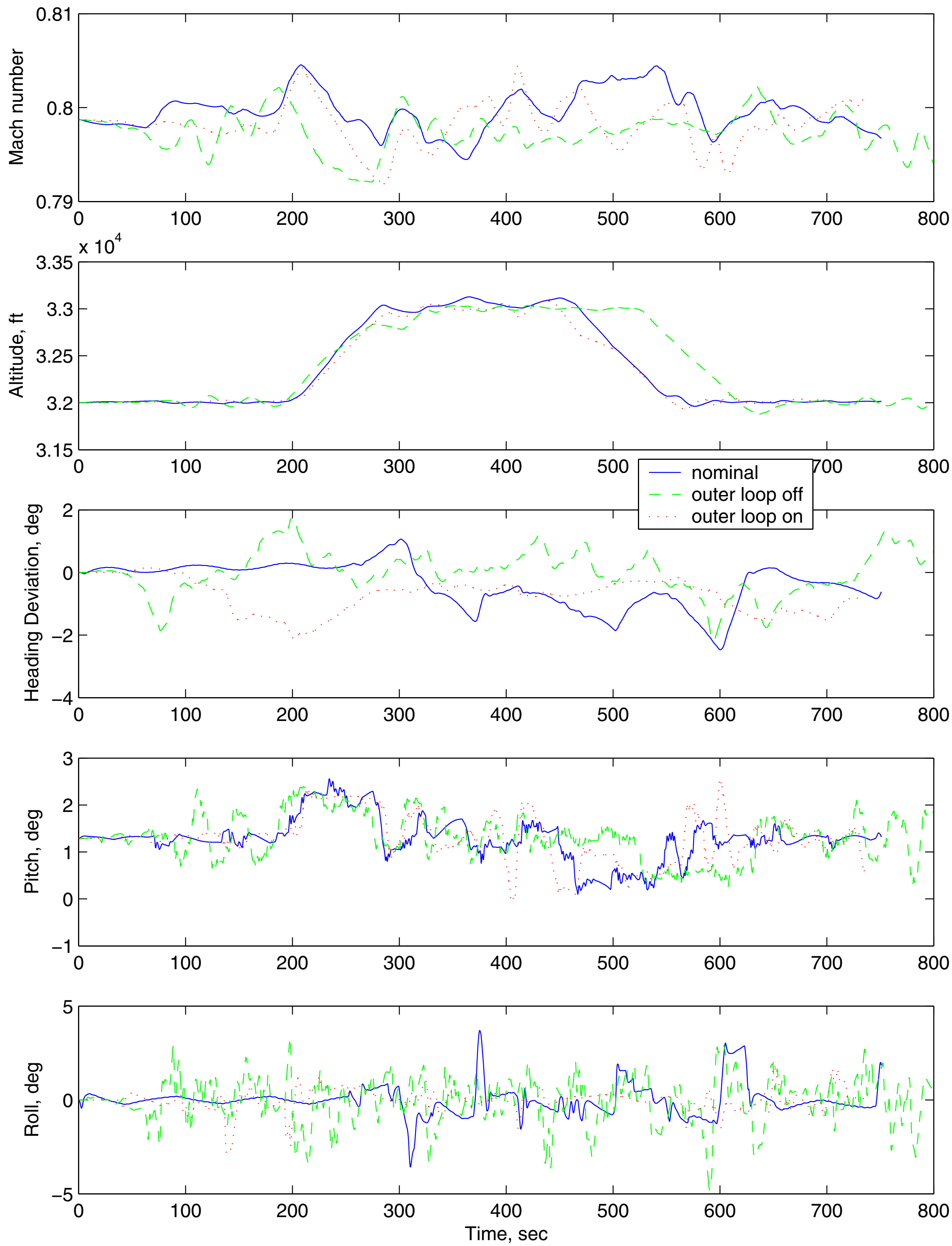

Figure 10.—Selected flight variables for transient flight with degradation in the front part of the engine.

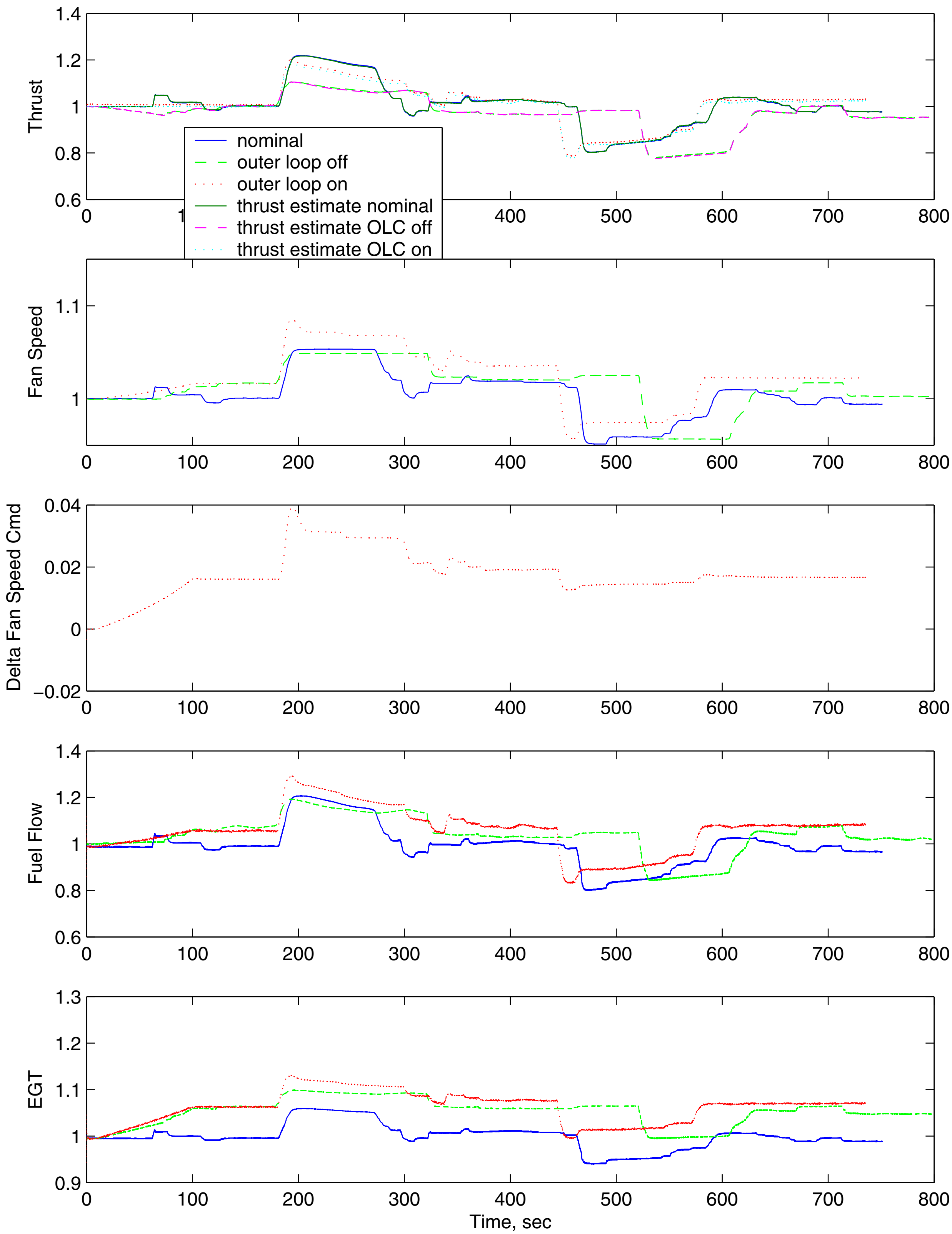

Figure 11.—Selected normalized engine variables for transient flight with degradation in the front part of the engine. OLC stands for outer loop control in the legend.

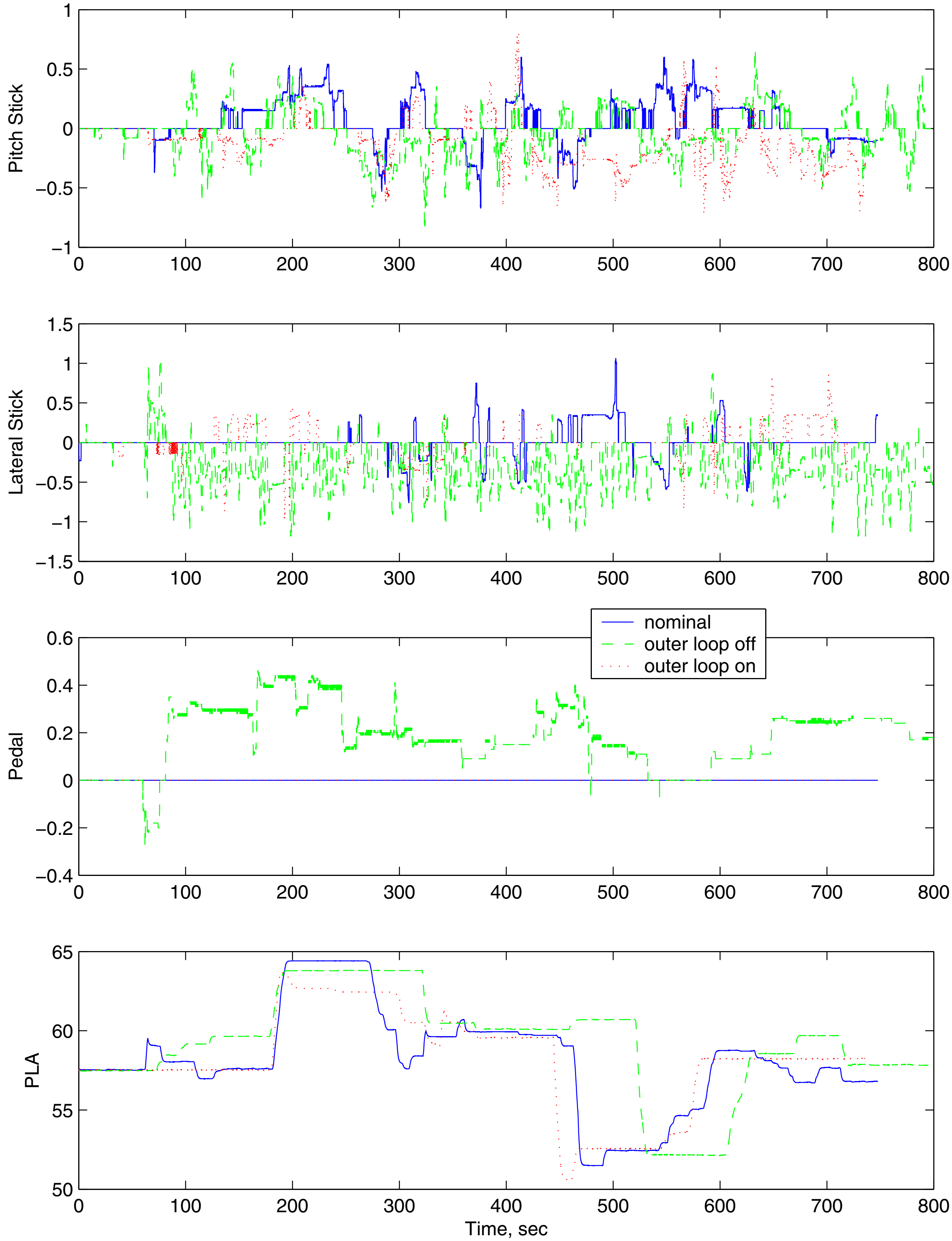

Figure 12.—Pilot inputs from a transient flight with degradation in the front part of the engine.

IV. Conclusions

The intelligent retrofit turbine engine control and diagnostics architecture implementation worked well in all cases evaluated and was shown to perform the duties that a pilot would otherwise need to do in compensating for the thrust imbalance, thus reducing workload. Such a system could be particularly useful on an instrument approach where heading is extremely important and the pilot is busy. When fully populated with diagnostic and Health Management algorithms as well as logic about the fan speed adjustments due to anomalies (this is the codification of pilot knowledge from training and flight manuals), such a system should be able to react to unusual situations within the operational limits of the engine. The incremental control commands added by the system enter the FADEC and as such are still subject to the controller's limit logic, preventing any undesigned-for operation of the engine. The independent adjustment of the fan speed settings is a new paradigm for pilots, who are trained to notice differences between engines and adjust the throttles separately until the fan speeds match. Of course this action in itself increases workload. The architecture greatly increases the autonomy of the propulsion system, and thus enables the concept of an Intelligent Flight Control/Mission Manager.

References

1. Litt, J.S., *et al*., "A Survey of Intelligent Control and Health Management Technologies for Aircraft Propulsion Systems," *Journal of Aerospace Computing, Information, and Communication* [online journal], vol. 1, no. 12, December 2004, pp. 543–563, URL: www.aiaa.org/jacic/, [cited 2 September 2005].
2. Roskum, Jan, *Airplane Flight Dynamics and Automatic Flight Controls, Part II*, Roskum Aviation and Engineering Corporation, 1979, Chapter 13.
3. Balut Ostrum, G., "Propulsion Aspects of the Thrust Asymmetry Compensation System (TAC) on the Boeing 777 Airplane," ASME paper 98–GT–457, International Gas Turbine & Aeroengine Congress & Exhibition, 43rd, Stockholm, Sweden, June 2–5, 1998.
4. AIA/AECMA Project Report on Propulsion System Malfunction Plus Inappropriate Crew Response Report (PSM+ICR), vol. 1, 1 November 1998, URL: http://www.faa.gov/aircraft/air_cert/design_approvals/engine_prop/engine_sp_topics/ [cited 30 August 2005].
5. Leveson, N.G., and Palmer, E., "Designing Automation to Reduce Pilot Errors," IEEE Systems, Man, and Cybernetics Conference, Orlando, FL, 12–15 October, 1997.
6. Sarter, N.B., Woods, D.D., and Billings, C. E., "Automation Surprises," *Handbook of Human Factors & Ergonomics*, *second edition*, edited by G. Salvendy, Wiley, 1997.
7. España, M.D., "Sensor Biases Effect on the Estimation Algorithm for Performance-Seeking Controllers," *Journal of Propulsion and Power*, vol. 10, no. 4, July-August 1994, pp. 527–532.
8. Kobayashi, T., and Simon, D.L., "Hybrid Neural-Network Genetic-Algorithm Technique for Aircraft Engine Performance Diagnostics," *Journal of Propulsion and Power*, vol. 21, no. 4, pp. 751–758.
9. Kobayashi, T., and Simon, D.L., "Application of a Bank of Kalman Filters for Aircraft Engine Fault Diagnostics," NASA/TM—2003-212526, ARL–TR–2955, GT2003–38550, August 2003.
10. Kobayashi, T., and Simon, D.L., "Evaluation of an Enhanced Bank of Kalman Filters for In-Flight Aircraft Engine Sensor Fault Diagnostics," *Journal of Engineering for Gas Turbines and Power*, vol. 127, July 2005, pp. 497–504.
11. Simon, D.L., "An Overview of the NASA Aviation Safety Program Propulsion Health Monitoring Element," AIAA–2000–3624, NASA/TM—2000-210348, ARL–TR–2272, 36th Joint Propulsion Conference and Exhibit, Huntsville, AL, July 16–19, 2000.
12. Bosco, C.J., "Certification Issues For Electrical and/or Electronic Engine Controls," SAE Paper 871844, Aerospace Technology Conference and Exposition, Long Beach, CA, Oct. 5–8, 1987.
13. Wohletz, J.M, Paduano, J.D., and Annaswamy, A.M., "Retrofit Systems for Reconfiguration in Civil Aviation," AIAA–99–3964, AIAA Guidance, Navigation, and Control Conference and Exhibit, Portland, OR, Aug. 9-11, 1999.
14. Monaco, J.F., Ward, D.G., and Bateman, A.J.D., "A Retrofit Architecture for Model-Based Adaptive Flight Control," AIAA–2004–6281, 2004 AIAA 1st Intelligent Systems Technical Conference, Chicago, IL, September 20–22, 2004.
15. Richards, N. D., *et al*., "Retrofit FDI and Adaptive Outer-Loop Control for Inflight Failure Accommodation," AIAA–2005–5935, AIAA Guidance, Navigation, and Control Conference and Exhibit, 15–18 August 2005, San Francisco, CA.
16. Bošković, J.D., Prasanth, R., and Mehra, R.K., "Retrofit Reconfigurable Flight Control," AIAA–2005–6374, AIAA Guidance, Navigation, and Control Conference and Exhibit, 15–18 August 2005, San Francisco, CA.
17. Litt, J.S., Parker, K.I., and Chatterjee, S., "Adaptive Gas Turbine Engine Control for Deterioration Compensation Due to Aging," ISABE–2003–1056, 16th International Symposium on Airbreathing Engines, Cleveland, OH, August 31–September 5, 2003.
18. Rausch, R., *et al*., "Towards In-Flight Detection and Accommodation of Faults in Aircraft Engines," AIAA 2004-6463, AIAA 1st Intelligent Systems Technical Conference, Chicago, IL, September 20–22, 2004.
19. Edmunds, J.M., "Control System Design and Analysis Using Closed-Loop Nyquist and Bode Arrays", *International Journal of Control*, vol. 30, no. 5, 1979, pp. 773–802.
20. Polley, J.A., Adibhatla, S., and Hoffman, P.J., "Multivariable Turbofan Engine Control for Full Flight Envelope Operation," 88–GT–6, Gas Turbine and Aeroengine Congress and Exposition, Amsterdam, June 5–9, 1988.

21. Litt, J.S., “An Optimal Orthogonal Decomposition Method for Kalman Filter-Based Turbofan Engine Thrust Estimation,” GT2005–68808, Proceedings of the 2005 ASME Turbo Expo, Reno-Tahoe, NV, June 6–9, 2005.
22. Volponi, A.J., “Gas Turbine Parameter Corrections,” *Journal of Engineering for Gas Turbines and Power*, vol. 121, October 1999, pp. 613–621.
23. Kurzke, Joachim, “Model Based Gas Turbine Parameter Corrections,” GT203-38234, Proceedings of 2003 ASME Turbo Expo, June 16–19, 2003.
24. Frankenberger, C.E., III, “Survivable Engine Control Algorithm Development (SECAD),” Proceedings of the 2002 IEEE Aerospace Conference, vol. 6, 2002, Big Sky, MT, March 9–16, 2002.
25. Lombardo, Giuseppe, and Torella, Giovani, “An Airborne Monitoring System for FOD and Erosion,” AGARD CP 55 8–19, AGARD, NATO, Rotterdam, April 1994.
26. Grindle, T.J., and Burcham, F.W., “Engine Damage to a NASA DC-8-72 Airplane from a High-Altitude Encounter with a Diffuse Volcanic Ash Cloud,” NASA/TM—2003-212030, August 2003
27. Brunell, B.J., Viassolo, D.E., and Prasanth, R., “Model Adaptation and Nonlinear Model Predictive Control of an Aircraft Engine,” GT–2004–53780, Proceedings of the 2004 ASME Turbo Expo, Vienna, Austria, 2004.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
December 2005

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
A Demonstration of a Retrofit Architecture for Intelligent Control and Diagnostics of a Turbofan Engine

5. FUNDING NUMBERS
WBS–22–303–30–72
1L161102AF20

6. AUTHOR(S)
Jonathan S. Litt, James A. Turso, Neerav Shah, T. Shane Sowers, and A. Karl Owen

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–15334

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001
and
U.S. Army Research Laboratory
Adelphi, Maryland 20783–1145

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—2005-214019
ARL–TR–3667
AIAA–2005–6905

11. SUPPLEMENTARY NOTES
Prepared for Infotech@Aerospace sponsored by the American Institute of Aeronautics and Astronautics, Arlington, Virginia, September 26–29, 2005. Jonathan S. Litt and A. Karl Owen, U.S. Army Research Laboratory, NASA Glenn Research Center; James A. Turso, QSS Group, Inc., 21000 Brookpark Road, Cleveland, Ohio 44135; Neerav Shah, NASA Glenn Research Center; and T. Shane Sowers, Analex Corporation, 1100 Apollo Drive, Brook Park, Ohio 44142. Responsible person, Jonathan S. Litt, organization code Z, 216–433–3748.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories: 07, 08, and 63
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)*

A retrofit architecture for intelligent turbofan engine control and diagnostics that changes the fan speed command to maintain thrust is proposed and its demonstration in a piloted flight simulator is described. The objective of the implementation is to increase the level of autonomy of the propulsion system, thereby reducing pilot workload in the presence of anomalies and engine degradation due to wear. The main functions of the architecture are to diagnose the cause of changes in the engine's operation, warning the pilot if necessary, and to adjust the outer loop control reference signal in response to the changes. This requires that the retrofit control architecture contain the capability to determine the changed relationship between fan speed and thrust, and the intelligence to recognize the cause of the change in order to correct it or warn the pilot. The proposed retrofit architecture is able to determine the fan speed setting through recognition of the degradation level of the engine, and it is able to identify specific faults and warn the pilot. In the flight simulator it was demonstrated that when degradation is introduced into an engine with standard fan speed control, the pilot needs to take corrective action to maintain heading. Utilizing the intelligent retrofit control architecture, the engine thrust is automatically adjusted to its expected value, eliminating yaw without pilot intervention.

14. SUBJECT TERMS
Propulsion control; Diagnostics; Flight path control; Artificial intelligence

15. NUMBER OF PAGES
24

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	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102