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"Summary"

Table of Contents

Navigating Around the Workshop:

[Workshop Home] [Session Agenda] [Submit Response / Read Responses]

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CONTENTS:

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NASA Dryden Flight Research Center

"Summary", page 1

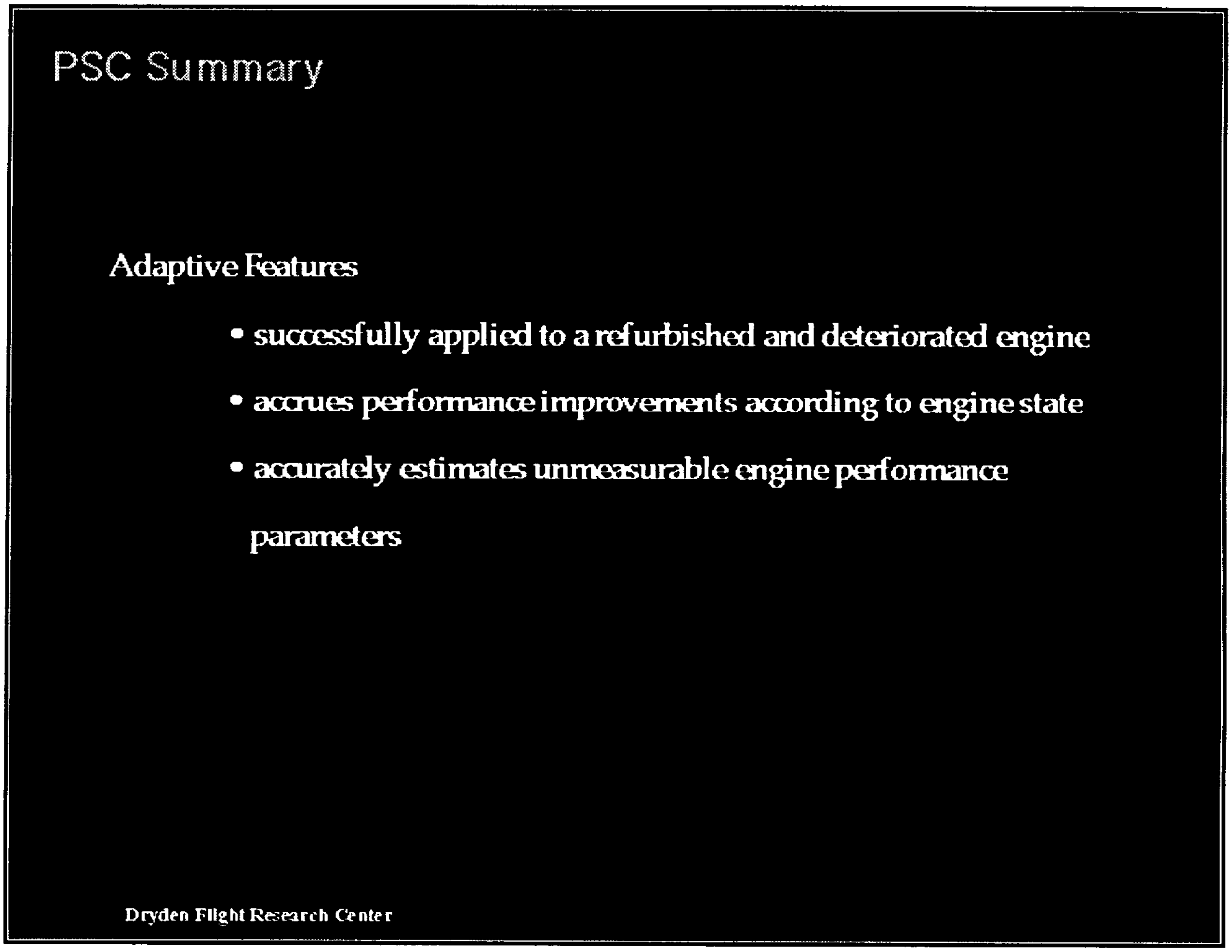
Adaptive Features

Navigating Around the Workshop:

[Workshop Home] [Session Agenda]

Paper [Index / Next] [Submit Response / Read Responses]

HELP is Available



PSC Summary

Adaptive Features

- successfully applied to a refurbished and deteriorated engine
- accrues performance improvements according to engine state
- accurately estimates unmeasurable engine performance parameters

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The Performance Seeking Control algorithm optimizes total propulsion system performance. This adaptive, model–based optimization algorithm has been successfully flight demonstrated on two engines with differing levels of degradation. Models of the engine, nozzle and inlet produce reliable, accurate estimates of engine performance. But, because of an observability problem, component levels of degradation cannot be accurately determined.

Depending on engine–specific operating characteristics PSC achieves various levels performance improvement. For example, engines with more deterioration typically operate at higher turbine temperatures than less deteriorated engines. Thus when the PSC maximum thrust mode is applied, for example, there will be less temperature margin available to be traded for increasing thrust.

Paper [Index / Next] [Submit Response / Read Responses]

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NASA Dryden Flight Research Center

"Summary", page 2

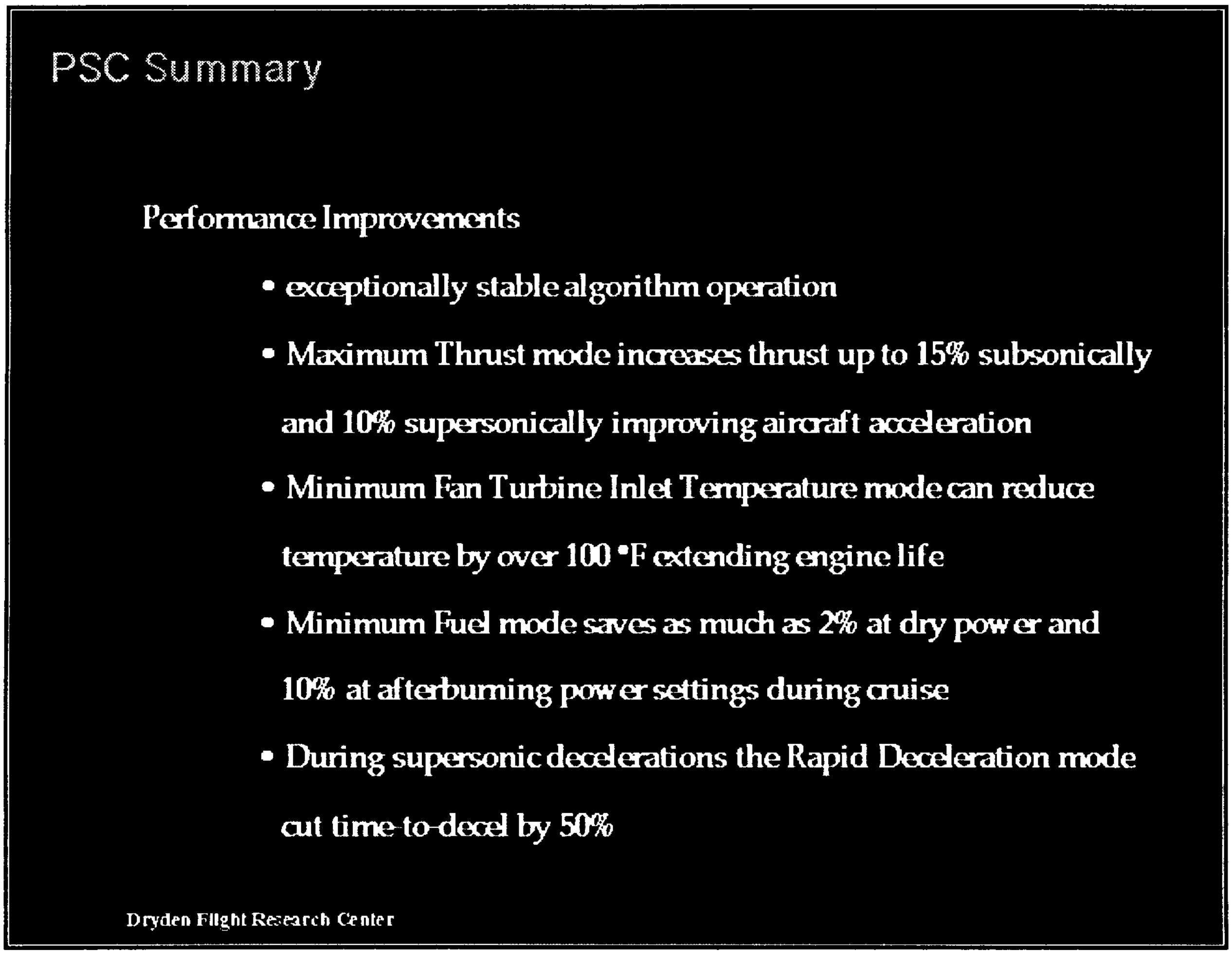
Performance Improvements

Navigating Around the Workshop:

[Workshop Home] [Session Agenda]

Paper [Index / Prev / Next] [Submit Response / Read Responses]

HELP is Available



PSC Summary

Performance Improvements

- exceptionally stable algorithm operation
- Maximum Thrust mode increases thrust up to 15% subsonically and 10% supersonically improving aircraft acceleration
- Minimum Fan Turbine Inlet Temperature mode can reduce temperature by over 100 °F extending engine life
- Minimum Fuel mode saves as much as 2% at dry power and 10% at afterburning power settings during cruise
- During supersonic decelerations the Rapid Deceleration mode cut time-to-decel by 50%

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Flight results show substantial benefits from the F−15 PSC algorithm. The PSC system benefits in general accrue from more accurate, real−time knowledge of various safety margins – that is, where the system currently is and where it can safely go. The PSC system takes advantage of this difference to maximize benefits. To its credit, the system operated in an exceedingly safe manner. No unrecoverable stalls, engine over–temps, or ingested shocks occurred over the 72 PSC test flights. In one instance, however, because of unsteady conditions, just after engaging the system, PSC caused a self–clearing pop–stall of the fan and immediately the system automatically disengaged. Also, during optimizations in which the fan turbine inlet temperature was driven to its maximum limit, the limit was exceeded transiently, but never more than by 10 deg.F. The pilots who flew with the PSC system characterize its operation as exceptionally reliable and were most impressed with its acceleration and deceleration performance.

In the Maximum Thrust mode, increases of up to 15 percent at subsonic and 10 percent at supersonic flight conditions were identified. Thrust increases were achieved essentially by trading available fan stall margin and operating at higher turbine temperatures. The Maximum Thrust mode reduced the time to accelerate by 15 percent at military power and between 4 and 7 percent at maximum afterburner. Performance improvements of this magnitude could be useful in a combat situation.

The Minimum Fan Turbine Inlet Temperature mode demonstrated temperature reductions exceeding 100 deg.F at high altitudes. If temperature were the only factor affecting engine life, these reductions would more than double engine life. In addition, lower operating temperatures could mean less required engine maintenance. The primary means of accomplishing the decreases in temperature were by reducing trim drag and lessening the thrust required for cruise.

Savings in fuel consumption of up to 2 percent in the subsonic regime and almost 10 percent supersonically were observed in the Minimum Fuel mode. Fuel consumption improvements like these could offer significant cost savings and/or range improvements to commercial airlines or the military. A large portion of the fuel savings are attained by down trimming the afterburner and also by reducing trim drag. Thrust was maintained in both the Minimum Fan Turbine Inlet Temperature mode and the Minimum Fuel mode as evidenced by the constant flight condition.

Supersonic decelerations with the PSC Rapid Deceleration mode produced dramatic results. At 45,000 feet, time to decelerate from Mach 2 to 1.1 was reduced by 50 percent. At 30,000 feet, time to decelerate was cut by approximately 30 percent. For in–flight emergencies, the benefits of this mode include increased controllability and safety. For military aircraft flying supersonic intercept missions, rapid deceleration gives the pilot increased control when engaging the adversary. Reducing infrared signature by lowering engine exhaust temperature may also be desired.

Overall, the PSC system can provide significant benefits for economy and performance. As a design tool, PSC could be used to reduce aircraft weight. PSC offers advantages to existing commercial subsonic and high performance military aircraft, as well as any future aircraft including the High Speed Civil Transport aircraft. For existing aircraft, PSC performance could be gained without any weight penalty. PSC could be used as a low cost and low weight retrofit to an entire class of aircraft. If PSC were incorporated in the design stage, the resulting configuration would reflect PSC's contribution by reductions in weight, maintenance costs, and performance.

Paper [Index / Prev / Next] [Submit Response / Read Responses]

NASA Dryden Flight Research Center

"Summary", page 3

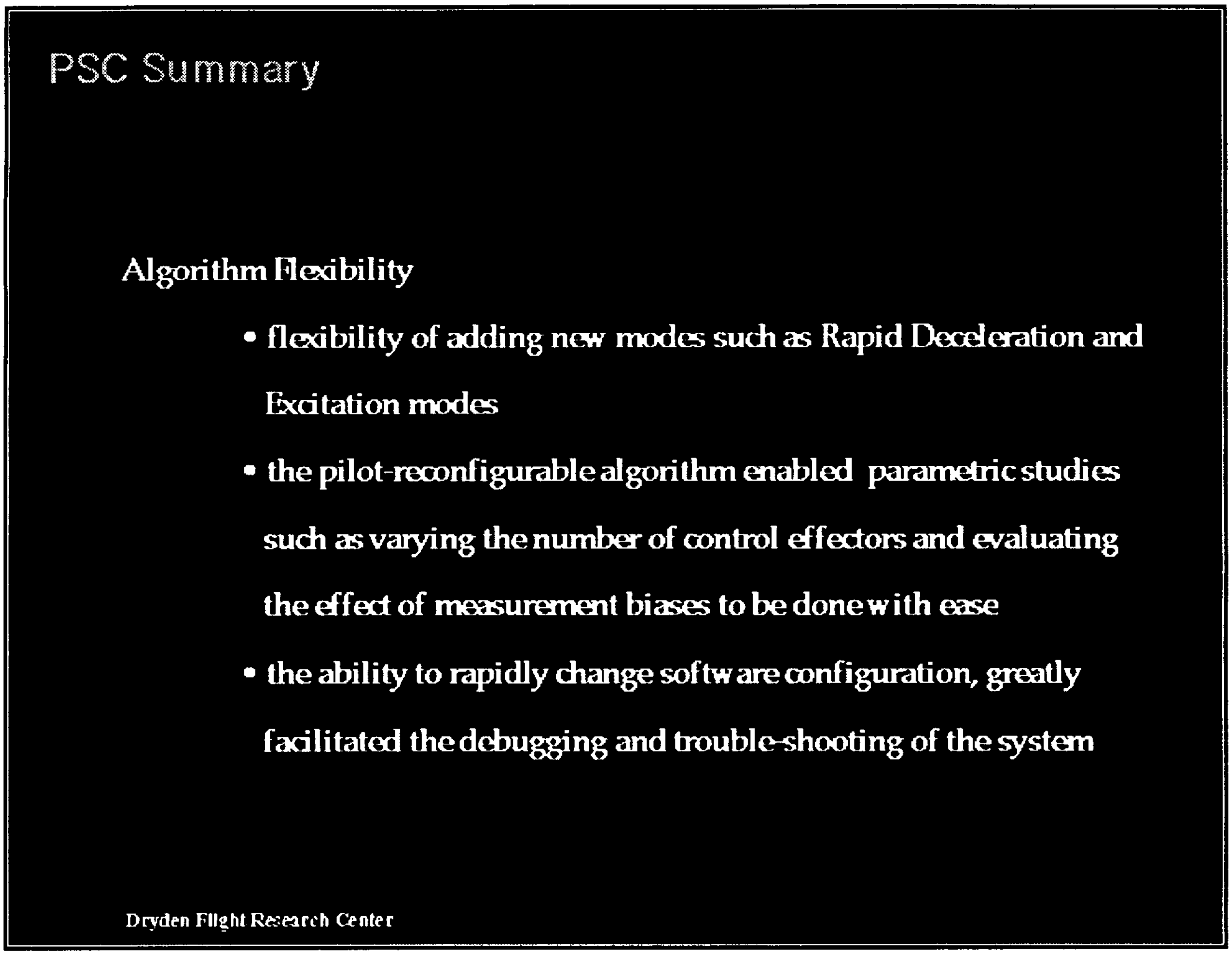
Algorithm Flexibility

Navigating Around the Workshop:

[Workshop Home] [Session Agenda]

Paper [Index / Prev / Next] [Submit Response / Read Responses]

HELP is Available



PSC Summary

Algorithm Flexibility

- flexibility of adding new modes such as Rapid Deceleration and Excitation modes
- the pilot-reconfigurable algorithm enabled parametric studies such as varying the number of control effectors and evaluating the effect of measurement biases to be done with ease
- the ability to rapidly change software configuration, greatly facilitated the debugging and trouble-shooting of the system

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The flexibility of the PSC algorithm, its architecture and implementation contributed greatly to a successful test program. The ability to rapidly change software configuration, greatly facilitated the debugging and trouble–shooting of the system. Two new modes which weren't even considered in the initial PSC design were added with very little difficulty, the Rapid Deceleration and PSC Excitation modes. The performance objective of the PSC algorithm can be changed very easily as was the case in the Rapid Deceleration mode where the performance index was just the opposite sign of the Maximum Thrust mode. In addition, the ability for the pilot select the algorithm configuration via the Navigation Control Unit (NCI) allowed for numerous parametric studies to be conducted. Changing the number of control effectors and the measuring the effect of biases, for example, would have been extremely cumbersome if a new OFP had to be released each time configuration changed.

Paper [Index / Prev / Next] [Submit Response / Read Responses]

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NASA Dryden Flight Research Center

"Summary", page 4

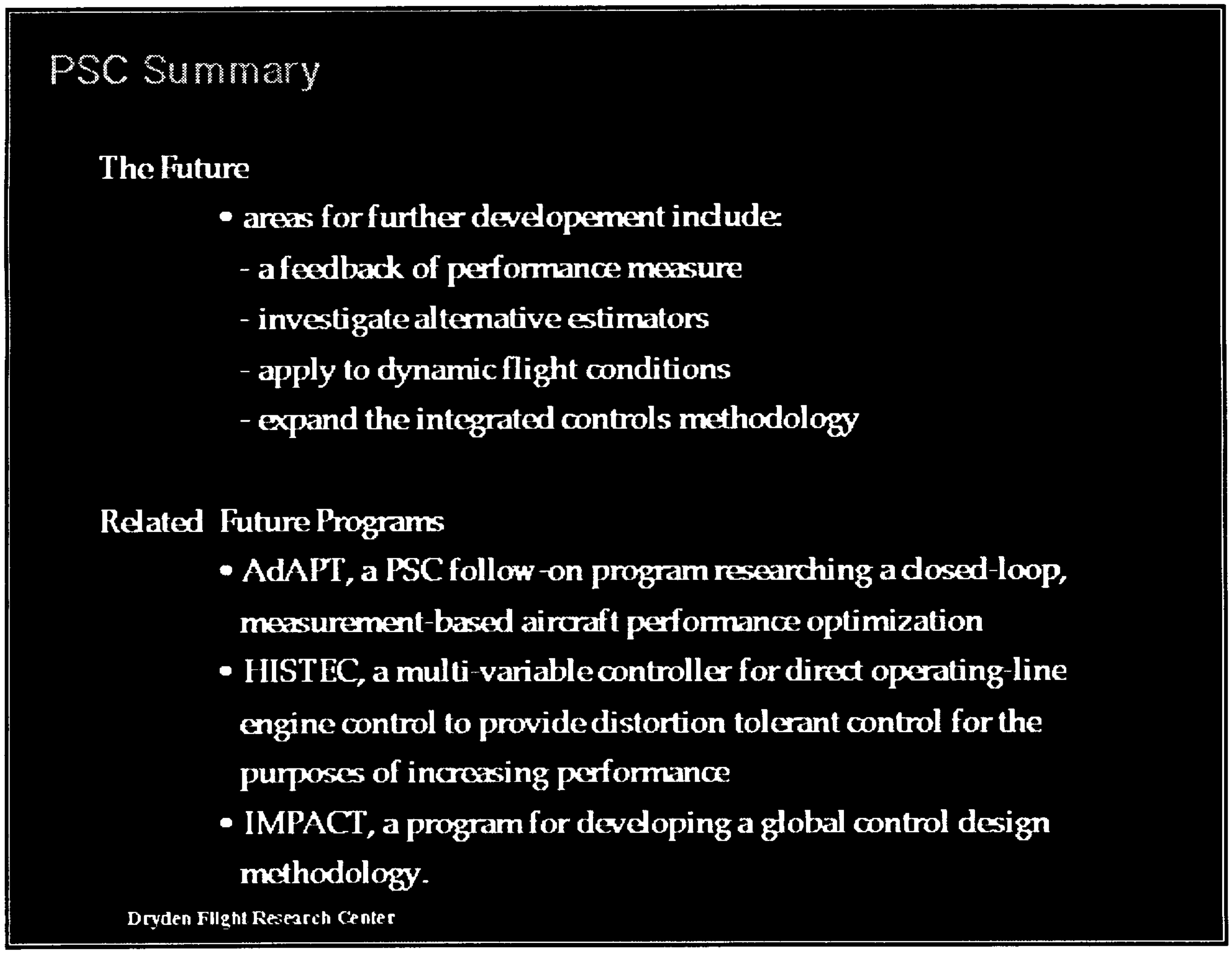
The Future

Navigating Around the Workshop:

[Workshop Home] [Session Agenda]

Paper [Index / Prev / Next] [Submit Response / Read Responses]

HELP is Available



PSC Summary

The Future

- areas for further developement include:
  - a feedback of performance measure
  - investigate alternative estimators
  - apply to dynamic flight conditions
  - expand the integrated controls methodology

Related Future Programs

- AdAPT, a PSC follow-on program researching a closed-loop, measurement-based aircraft performance optimization
- HISTEC, a multi-variable controller for direct operating-line engine control to provide distortion tolerant control for the purposes of increasing performance
- IMPACT, a program for developing a global control design methodology.

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The F-15 PSC program developed a technical approach and methodology that can enhance the performance of high-performance and transport aircraft. The PSC algorithm as it was implemented on the F–15, however, requires accurate models that predict actual flight hardware performance operation. In addition, the adaptive estimation technique depends on accurate measurements of the inputs and outputs of the system being optimized. Because of the model–based open–loop approach used by the F–15 PSC, errors in modeling and measurements produce estimated optimal trim commands rather than measurement–based, true optimal trim commands. To improve system performance, several improvements could be made. By increasing the number of measurements and adding feedback, the system would rely less on the models and would simultaneously improve modeling accuracy. Alternative estimators to the Kalman filter should also be explored; the dynamic Kalman filter employed for PSC was unnecessarily complicated and had an observability problem. At some point in the future, it mat be desired to expand the valid aircraft maneuvering envelope for PSC beyond just quasi steady–state to more dynamic conditions. It would also be of interest to expand the integrated controls methodology to include more direct aerodynamic control effectors in the PSC optimization such as stabilator and ailerons.

Some of the areas for further research mentioned above are currently being addressed in related programs. A joint NASA, USAF, MDA, and P&W program called Adaptive Aircraft Performance Technology (AdAPT) is a follow–on PSC project. AdAPT will continue to advance the optimal performance technology base with a performance optimization algorithm that is measurement–based and includes feedbacks. The modified F–15 Short Take–off and Landing/Maneuvering Technology Demonstrator (S/MTD) aircraft will be used to demonstrate this technology. Initial planning is directed at quasi–steady optimization modes such as minimum fuel consumption at constant thrust or maximum thrust for a fixed fuel flow. The AdAPT optimization approach uses measurement feedback of performance metrics to ensure optimality. The AdAPT algorithm primarily optimizes with aerodynamic effectors to achieve its results, but also will control an axi–symmetric pitch/yaw vectoring nozzle.

Two other planned programs are related to the PSC research. The High Stability Engine Control (HISTEC) will investigate a multi–variable controller for direct operating–line engine control to provide distortion tolerant control for the purposes of increasing performance. Integrated Methodology for Propulsion and Airframe Control Technology (IMPACT) is a program for developing a global control design methodology. The idea of IMPACT is to capitalize on the inherent coupling between the engine and airframe.

Paper [Index / Prev / Next] [Submit Response / Read Responses]

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NASA Dryden Flight Research Center

"Summary", page 5

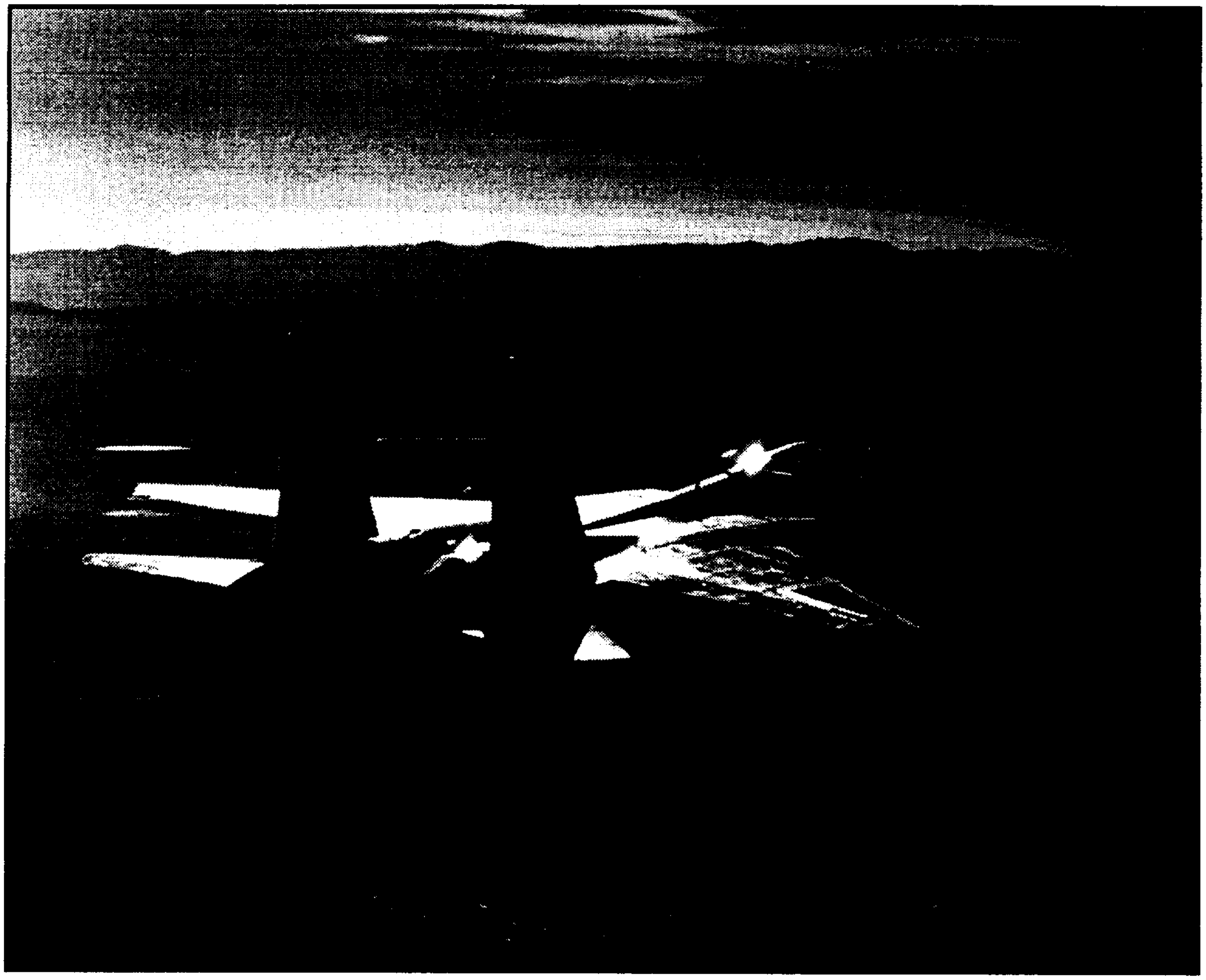
Final Thoughts

Navigating Around the Workshop:

[Workshop Home] [Session Agenda]

Paper [Index / Prev] [Submit Response / Read Responses]

HELP is Available



The Performance Seeking Control experience is an excellent example of how flight test research benefits emerging technologies. The close–knit relation between working partners in government and industry has been mutually beneficial. From the PSC flight test program a high risk technology was demonstrated and matured to the extent that industry is already commercializing it. The typical development cycle time for a new high risk technology such as PSC is anywhere from 7 to 10 years. Even before the test program ended in 1993, portions of the PSC technology were being incorporated as a standard part of new military aircraft engines. This demonstrates the value of flight test research. The government gained experience with a new technology and fulfilled its mission of technology transfer. Without NASA's aid, MDA and P&W probably would not have developed the PSC technology to the point where commercial products result because the costs and risks are just too high.

Paper [Index / Prev] [Submit Response / Read Responses]

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PCA Session Information

As a result of several accidents in which all or major parts of the flight control system was lost, NASA Dryden investigated the capability for a "Propulsion Controlled Aircraft" (PCA) system, one which used only engine thrust for flight control.

Initial flight studies with the pilot manually controlling the throttles and all flight controls locked in the NASA F-15 showed that it was possible to maintain gross control. For instance, a climb could be initiated by adding an equal amount of power to both engines. Bank control could be achieved by adding power to one engine and reducing power to the opposite engine. Using these techniques, altitude could be maintained within a few hundred feet and heading to within a few degrees. These same flights showed that it was extremely difficult to land on a runway. This was due to the small control forces and moments of engine thrust, difficulty in controlling the phugoid oscillations, and difficulty in compensating for the slow engine response. Studies in flight simulators at Dryden and at McDonnell Douglas were able to duplicate the flight results. These simulators also established the feasibility of a PCA mode, shown below, using feedback of parameters such as flight path angle and bank angle to augment the throttle control capability and to stabilize the airplane.

The NASA F-15 was an ideal testbed airplane for this research. The HIDEC digital engine controls, digital flight controls, general-purpose computer and data bus architecture minimized the equipment that had to be added for PCA. The only equipment added to the airplane was a control panel containing 2 thumbwheels, one for flightpath command, and the other for bank angle command. These papers will describe the design, development, and flight test results.

Agenda

Frank W. Burcham Jr., "Background and Principles of Throttles-Only Flight Control"

Edward A. Wells, James M. Urnes, Sr., "Propulsion Controlled Aircraft Design and Development"

Frank W. Burcham Jr., Trindel A. Maine, "Flight Test of a Propulsion Controlled Aircraft System on the NASA F-15 Airplane"

Stephen Corda, Mark T. Stephenson, Frank W. Burcham Jr., "Dynamic Ground Effects Flight Test of the NASA F-15 Airplane"

PCA Session Information (Concluded)

Agenda (Concluded)

Trindel A. Maine, Frank W. Burcham Jr., Peter Schaefer, John Burken, "Design Challenges Encountered in the F-15 PCA Flight Test Program"

Frank W. Burcham Jr., "F-15 PCA Conclusions and Lessons Learned"

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