1. AN OVERVIEW OF NASA'S DIGITAL FLY-BY-WIRE TECHNOLOGY DEVELOPMENT PROGRAM

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SUMMARY

The feasibility of using digital fly-by-wire systems to control aircraft was demonstrated by developing and flight testing a single channel system, which used Apollo hardware, in an F-8C test airplane. This is the first airplane to fly with a digital fly-by-wire system as its primary means of control and with no mechanical reversion capability. The development and flight test of a triplex digital fly-by-wire system, which will serve as an experimental prototype for future operational digital fly-by-wire systems, is underway.

INTRODUCTION

The advantages of digital fly-by-wire (DFBW) systems in terms of control system flexibility and reliability were demonstrated for spacecraft applications in NASA's manned space program. However, the transfer of this technology from spacecraft to aircraft is not direct and will require the identification and solution of many problems.

DFBW technology, when fully utilized in the flight control system of an aircraft, can provide significant advantages over conventional control systems in terms of reduced costs, weight, and volume, and in improved performance. A redundant digital system, which can identify in-flight system failures and reconfigure itself, offers a potential reliability comparable to that of the basic aircraft structure as well as the advantages of automatic control techniques.

Although these benefits cannot be easily quantified for all classes of aircraft, design studies do indicate major rewards in terms of more effective flight control systems and, thus, more effective aircraft. But even more important, these systems lay the ground work for active control technology, and it is the active-control-configured aircraft that offers the greatest potential in economic gains and performance advancements.

The overall objective of NASA's digital fly-by-wire program is to provide the foundation for this technology, in terms of design criteria and operational experience, which will lead to the development of practical digital fly-by-wire systems for future aircraft. To accomplish this objective, the program was separated into two phases, with an F-8C airplane (fig. 1) used as the test vehicle.

The goal of Phase I, which has been accomplished, was to demonstrate the feasibility of using a DFBW system as the primary flight control system of an aircraft. To accomplish this goal, a single channel DFBW primary flight control system was flight tested, using an analog backup control system for fail/safe redundancy.

The goal of Phase II is to establish a design base for the development of practical DFBW systems. This will involve the development and flight test of a triplex DFBW system using redundancy management and data bus concepts.

Figure 2 shows the schedule for Phases I and II. The major aspects of each phase are discussed in the following sections.

SINGLE CHANNEL SYSTEM DEVELOPMENT

To establish the feasibility of the DFBW concept, a system was designed to replace the basic mechanical primary flight control system of the F-8C test airplane in all three control axes. All mechanical connections linking the pilot's control stick and rudder pedals to the control surfaces were removed. To be compatible with fly-by-wire design philosophy and development practice, no mechanical reversion capability was provided even during the first part of the flight-test program. This is particularly significant because it required that satisfactory design and test techniques be demonstrated before the first flight. A single channel digital system concept was selected as the most straightforward approach to establishing system feasibility.

To minimize cost and development time, digital hardware and software originally developed for the Apollo program were used as the heart of the digital system. An Apollo guidance and navigation system was used which consisted of a digital guidance computer, an inertial measurement unit, and associated interface elements. Use of this hardware also made available highly trained Apollo support teams. Another factor leading to the selection of the Apollo computer was its demonstrated 70,000-hour mean-time-before-failure record. This factor overrode shortcomings of the hardware which resulted in some operational constraints.

A more complete description and discussion of the digital system is presented in paper 2. Pertinent aspects of man-rated software are covered in paper 4.

To provide redundancy if the primary digital system failed, an analog flight control system from a lifting body research vehicle was modified extensively and installed in the F-8C airplane as a triplex analog backup control system (paper 3).

Phase I began in January 1971. During the following 15 months, five major contractors took part in the development and flight qualification of the Phase I system. These contractors and their areas of responsibility were:

Delco Electronics	Digital system hardware
The Charles Stark Draper Laboratory, Inc. (MIT)	Digital system software
Sperry Flight Systems Division	Analog backup control system
Hydraulic Research and Manufacturing Company	Secondary actuators
Ling-Temco-Vought, Inc.	Aircraft and electrical systems

In addition to control law design and contractor coordination, NASA was responsible for specifying the Phase I system baseline configuration and interface requirements, verifying the final software and hardware flight readiness, and conducting the flight tests.

The Phase I system was first used in flight on May 25, 1972. This was the first flight of an aircraft in which a digital fly-by-wire flight control system was the primary means of control. As noted previously, no mechanical reversion capability was provided. Confidence in the reliability of the digital system was demonstrated by using it on the first takeoff and landing.

Forty-two flights were made before the flight program was completed in November 1973. The total flight time was 58 hours. The pilot controlled the airplane most of this time using the primary digital system. Approximately 14 hours were flown using the analog backup system for evaluation purposes, inasmuch as no digital system failures were experienced during flight. The flight-test results are presented in papers 3 and 6.

Phase I established the feasibility of DFBW systems for primary aircraft control and provided flight data related to control law design, software verification, and operational procedures for DFBW systems.

MULTICHANNEL SYSTEM DEVELOPMENT

The goal of Phase II is to establish a design base for the development and implementation of future practical DFBW systems. To accomplish this goal a multichannel system is being developed which will provide redundancy management flight-test experience and verify other concepts of particular concern to the space shuttle orbiter development.

The Phase II system configuration and major tasks are discussed in the following sections.

System Configuration

A simplified diagram of the fully redundant triplex DFBW system is shown in figure 3. The principal elements of the system are to be installed on a removable pallet assembly, as the single channel system was in Phase I. Major components developed for Phase I, such as the analog backup control system, redundant secondary actuators, electrical power system, and instrumentation system, are to be retained for use during Phase II.

Dedicated, redundant sensors will be used to measure airplane angular rate, attitude, acceleration, and air data. Sensor inputs will be cross-strapped to each computer and synchronized on a bit-by-bit basis. Surface command outputs will be voted for fault detection and supplied to the triplex, force-summed, secondary actuator servo valves. Differential pressure equalization will be used to minimize nonlinear secondary actuator effects. A two channel (active and monitor) analog backup control system will be provided for use if the primary system fails.

The system will be designed to minimize ground operational and preflight support requirements. All system status testing will be automated and will be done onboard the airplane.

The digital processor selected for Phase II is a state-of-the-art, off-the-shelf, general-purpose computer with floating-point and microprograming features. The computer is an order of magnitude faster than the Apollo computer used in Phase I. The main storage memory is fully programable, which provides greater software flexibility. This increase in computer capability is of particular importance in carrying out the objectives of the Phase II program.

Evaluation of Space Shuttle Orbiter DFBW Concepts

An important aspect of Phase II is coordination with the shuttle orbiter flight control system development. In addition to being the first application of DFBW in an aerodynamic vehicle, the orbiter will contribute significantly to digital system technology by addressing the problems of redundancy management (reliability) and overall mechanization.

The shuttle flight control system will use the same digital processors as those being used in Phase II of the F-8 DFBW program. The Phase II triplex processor/sensor configuration will thus make it possible to evaluate certain aspects of the shuttle system by using the F-8C airplane as a test-bed.

Redundancy management.— The redundancy management concept developed for the orbiter system to detect and isolate digital processor and control system sensor failures will be implemented and flight tested during Phase II. Because a reliable means of achieving failure detection and isolation is a major problem in the design of redundant DFBW systems, flight-test verification of the concepts in Phase II will establish a significant data base for future applications.

Data bus.— The data bus concept of reducing cabling and connector requirements for redundant systems by compressing data from several sensors onto redundant transmission lines is important in the development of DFBW technology. The discrete format of signals in DFBW systems makes the data bus a natural solution to the complex cabling problem. In Phase II the technique proposed for the shuttle system will be used to process trim commands and mode panel information (e.g., status lights, mode change commands) and to transmit the information from the airplane cockpit to the palletized system in the equipment bay. This will greatly reduce the number of wires and will verify data bus utility for shuttle as well as future system applications.

Computer synchronization. – Of major concern in the design of any redundant DFBW system is whether or not to synchronize the computer operations and, if so, the best way to do it. The Phase II system will be designed with enough flexibility to permit the use of various synchronization approaches as well as asynchronous operation. Included will be the baseline approach selected for the orbiter system.

Control laws. – The first control laws to be evaluated in flight during Phase II will be similar to those developed for the F-8C airplane during Phase I and similar in format to those being developed for the shuttle orbiter. These include C* and rate command modes for pitch and roll as well as direct control modes for each axis. Control law software required for moding and initialization will therefore be similar for both programs, which will permit some system verification.

Higher order programing language. – A higher order programing language, called Higher Aerospace Language (HAL), is being developed in support of shuttle software requirements. Use of this language in developing certain elements of the control laws for the Phase II system will make it possible to debug and verify it before it is actually applied to the shuttle orbiter.

Backup control system. – The present shuttle system configuration will require a dissimilar single channel digital backup control system during initial horizontal flight tests to override possible primary system generic failures. The executive structure for the shuttle backup system will be implemented in the Phase II system and flight-qualified through flight-test verification.

Advanced Control Law Development

To assess the capability of a digital system to perform the functions necessary for future active control applications, additional control laws will be programed and evaluated during Phase II. A specific task is the investigation of improvements that can be made in aircraft control law implementation as a result of the rapidly advancing digital fly-by-wire system capability. The availability of a powerful onboard digital computer system that can process sophisticated flight control laws in real time has added a new dimension to realizable control law development. Control laws previously too complex and unwieldy for analog system applications can now be considered prime candidates for digital applications.

Initial Phase II control law research is directed toward the use of active control for maneuver load control, possible improvement in ride quality, suppression of turbulence effects, flight envelope limiting techniques, and operation at reduced static-stability margins. The basic elements of such a control law now being developed for the longitudinal axis are illustrated in figure 4. The structure consists of a boundary controller for angle-of-attack limiting, a normal controller for longitudinal commands, a direct-lift controller for commanding symmetric ailerons, a load controller, and autopilot modes. A proportional flap-to-elevator crossfeed is planned to compensate for the pitching moment produced by symmetric aileron deflection.

The design objective for the longitudinal axis is to achieve good handling qualities by matching desired response criteria for both positive and negative static stability margins. Gust load alleviation is provided by additional damping of short-period dynamics using the elevator surface. Angle-of-attack limiting is provided throughout the flight envelope.

Direct lift of the symmetric ailerons is combined with the elevator to minimize drag during maneuvers and to enhance gust load alleviation during cruise. The three autopilot modes are the conventional attitude hold, altitude hold, and Mach hold.

Other advanced control law prospects, in which adaptive techniques and optimal control theory are used, are being studied for possible flight-test evaluation during Phase II.

Remotely Augmented Vehicle Facility

As part of Phase II, a unique remotely augmented vehicle facility is to be developed to support advanced control law research and flight-test evaluation. A diagram of the proposed facility is shown in figure 5. During a test flight, a special remotely augmented vehicle test mode may be selected by the pilot that will divert his control commands to a ground computer facility, via a telemetry down-link, on which a particular advanced control law to be evaluated is programed. Control surface commands are determined by the ground computer on the basis of the pilot's airborne commands, the airplane's response, and the programed control law. The surface commands are then transmitted, via a telemetry up-link, to the airplane system and the corresponding control surface. The pilot flies the airplane through the control laws programed on the remotely located ground computer. Fail safety will be maintained through the use of reasonability tests built into the ground computer facility and safety networks in the telemetry equipment. This approach will permit a great deal of flexibility for control law evaluation without compromising the basic airborne system verification requirements.

CONCLUDING REMARKS

The full realization of the benefits of active control technology and the benefits predicted by its application to aircraft design depends on the development of practical, reliable, and versatile digital fly-by-wire (DFBW) control systems. The feasibility of such systems and confidence in their reliability and integrity were established in Phase I of the F-8 DFBW program. The goal of Phase II of the program is to establish a design base from which practical, reliable systems can be developed. This will be accomplished by developing and flight testing a fully redundant triplex DFBW system.

The multichannel system development carried out during Phase II will establish techniques for validating redundant system software and hardware interfaces and for establishing operating procedures unique to DFBW systems. Flight-test evaluation of orbiter control system concepts using the F-8C airplane will result in verification of redundancy management software for digital processor and sensor fault detection and reduced generic failure probabilities for the orbiter system.

Flight-test evaluation of advanced control laws during Phase II will provide an opportunity to assess the capability of DFBW systems to perform the complex control tasks associated with active control applications.

The NASA DFBW program, although complementary to other fly-by-wire activities, is aimed specifically at providing the technology for practical digital flight controls for civil aircraft. As such, it represents the first step toward a new generation of active-control-configured aircraft which will offer significant economic advantages.

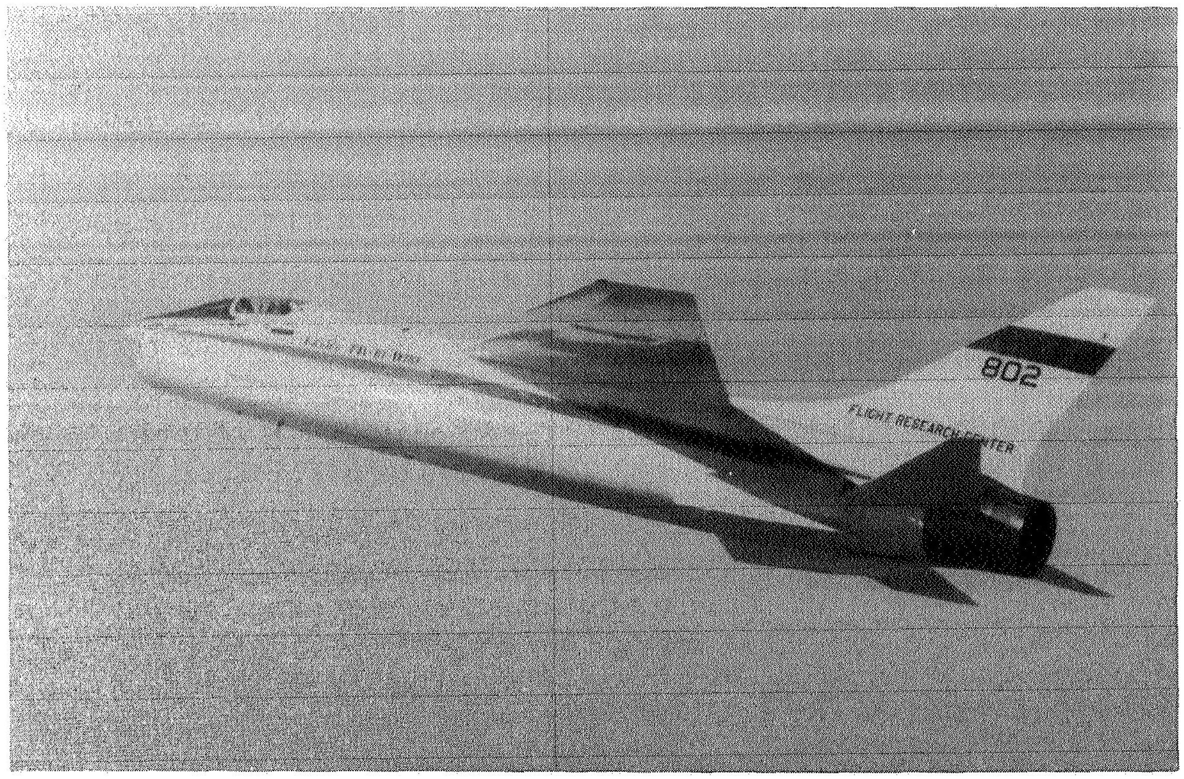

Figure 1. F-8C test airplane.

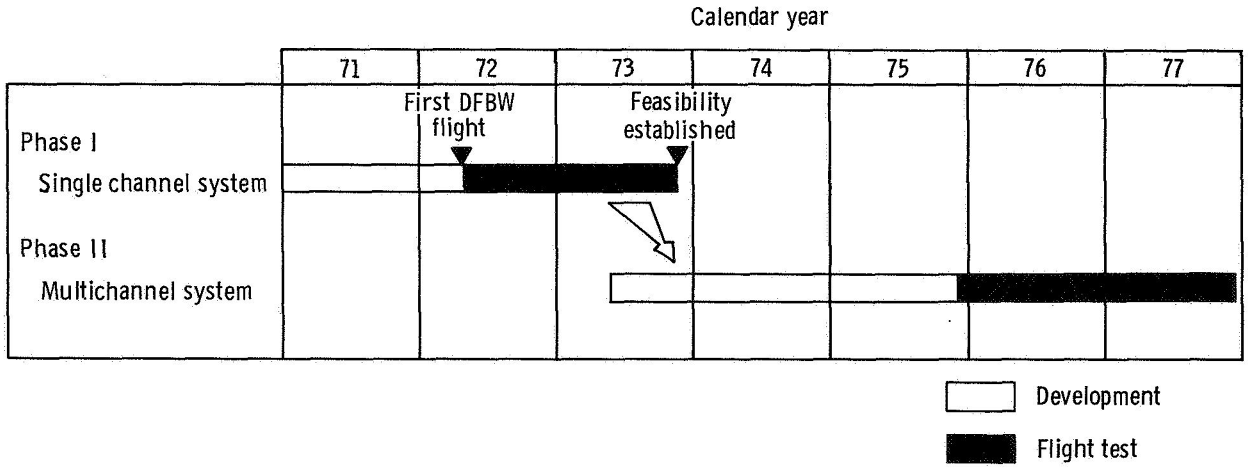

Figure 2. F-8 DFBW program schedule.

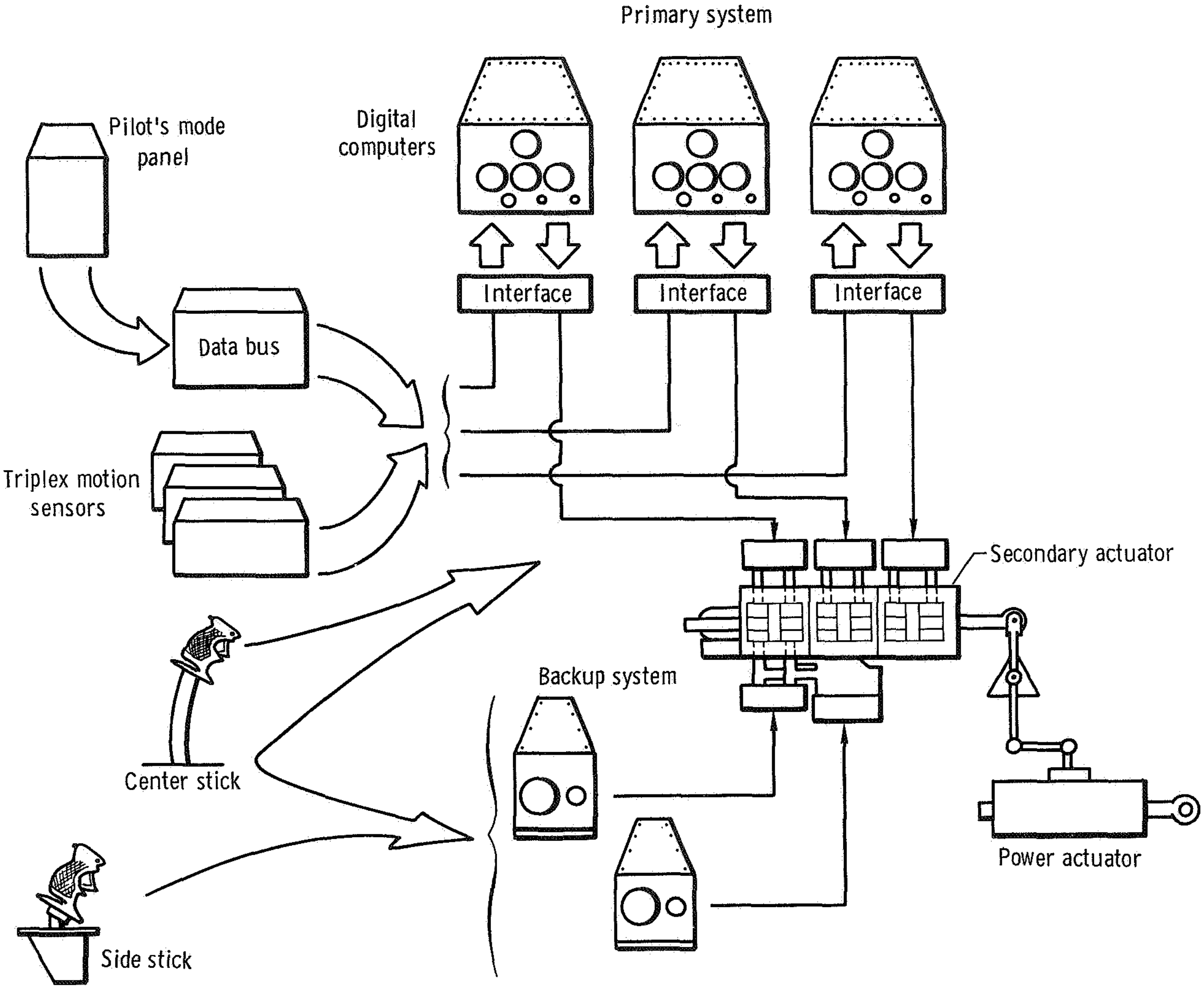

Figure 3. Phase II system configuration.

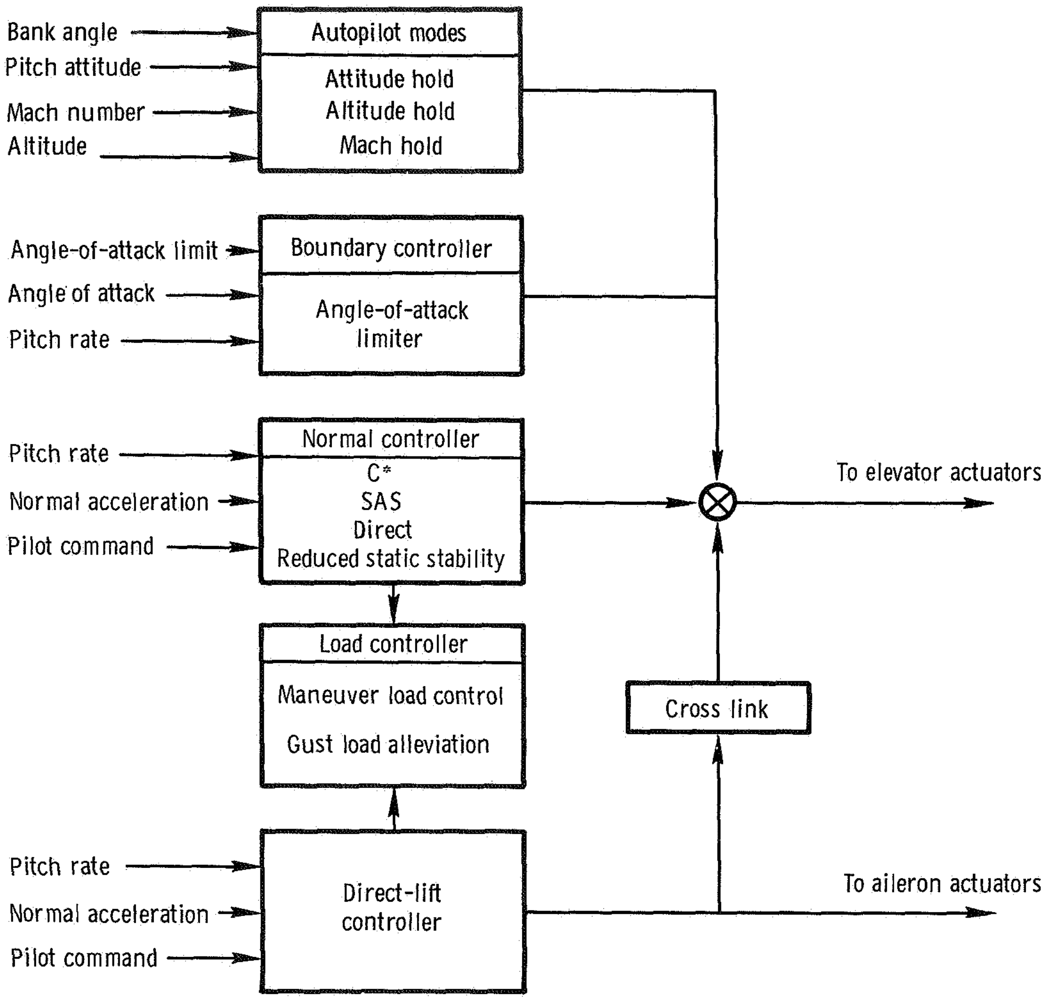

Figure 4. Active control law diagram for longitudinal axis.

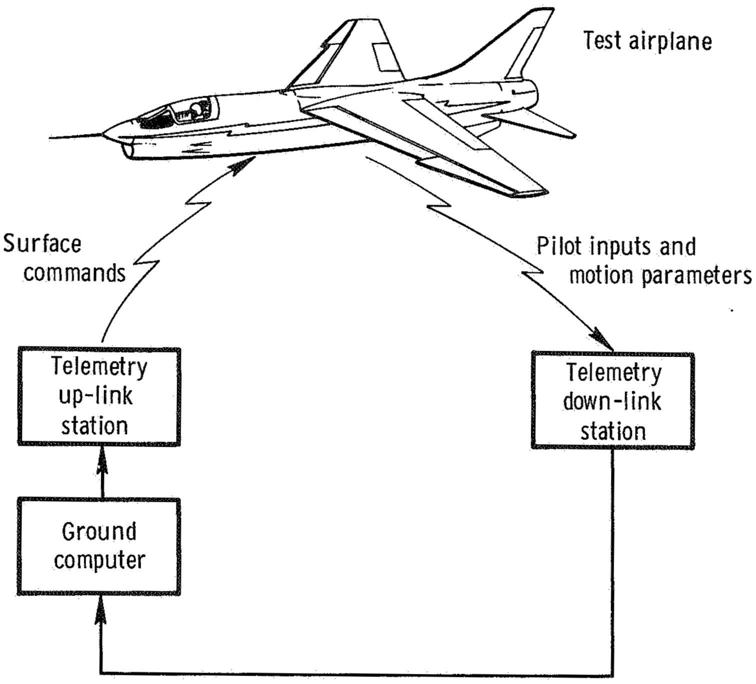

Figure 5. Remotely augmented vehicle facility.