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A LOOK AT DIGITAL NOSE WHEEL STEERING

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Flight Systems Engineering

24 September 1990

Final Report for Period February 1990 - August 1990

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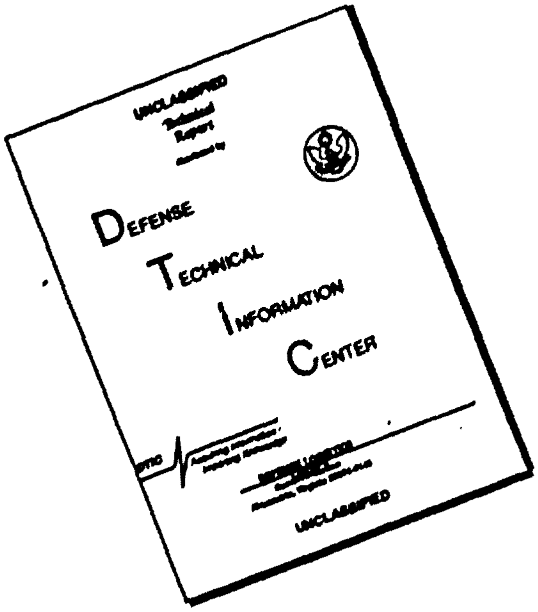

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This report examines the impact of digital control on nose wheel steering of aircraft. The development of steering systems is reviewed from early mechanical systems through integrated brake control systems. The value of digital control is then examined based on unique capabilities, performance improvement, and fault detection. Cost, weight, and maintainability impacts are discussed.

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Contents

Overview

This report assesses the relative merits of digital nose wheel steering (NWS) as compared to analog systems. The assessment is intended as an aid to landing gear systems engineers who are faced with choosing a type of NWS control system. Methods of aircraft ground directional control are reviewed to understand the widely varying requirements that are placed on NWS. The ability of digital NWS to meet these requirements constitutes the main sections of the report.

Why Use a Nose Wheel to Steer an Aircraft

NWS serves two basic purposes: taxi maneuvering and landing (or takeoff) control. Taxi steering may optionally be done by differential braking and thrusting. Steering for landing at high speeds may be done with aerodynamic surfaces and at low speeds with differential braking.

With alternate forms of steering available, why worry about a NWS system that adds weight and complexity to an aircraft? Three reasons exist.

First, NWS serves as an alternate system to differential braking or thrusting. This may be important when brakes are too hot or malfunctioning and when differential thrusting is not practical.

Second, sometimes a lack of NWS may be dangerous. For example, thrust reversing a fighter may significantly yaw the aircraft. This may be accompanied by reduced aerodynamic surface control authority and reductions in wheel loadings which may further reduce aircraft controllabilty (Young and Ohly, 1985:6,8). On aircraft with bicycle type main gear such as the U-2 and Harrier, differential braking is not available so NWS must be used.

An additional danger occurs with the blowout of a main gear tire on an aircraft which will result in significant lean. This lean may generate significant cornering forces. The resulting directional uncontrollability may result in dangerous situations such as departure form the runway. A steered nose wheel or a drag chute are about the only solutions (Daugherty and Stubbs, 1985).

The third reason for using NWS is the need for improved performance. A dangerous situation occurs when landing yawed to the runway or in high crosswinds. Such landings require some form of special directional control. In large aircraft this may be a turning of the main gear to match the yaw angle and nose wheel steering may or may not be used. Small aircraft generally de-yaw on touchdown in moderate crosswinds. The next generation aircraft may require yawed landing capability for higher crosswinds and to land in a damaged condition or on short and wet runways (Smith and others, 1985; Zaiser, 1989).

Arguments against NWS may be found in the weight, maintainability, and safety concerns resulting from the use of NWS. The weight and maintainability problems arise from the addition of the NWS hydraulic and control systems to the aircraft. The safety concerns result from effects of a NWS failure. Early F-4 and F-16 aircraft suffered from "hard over" failures causing the nose wheel to travel to the extreme right or left position, occasionally resulting in departure from the runway.

Historically, NWS development has involved a lot of trial and error during system development. Once developed, old systems are often adapted for use on new aircraft, for example F-4 gear on the Tornado, and T-39 NWS on the F-16. As a result, NWS is a relatively well understood older technology undergoing slow evolutionary change. Older hardware, while well understood, does not take advantage of more reliable and better performing newer components.

In spite of relatively low levels of interest, NWS research and development continues to go on as part of other programs such as improved landing and development of a specific aircraft. As part of these programs, techniques for integrating NWS, braking, and aerodynamic control surfaces have been developed and tested.

Aircraft control systems in general are tending to be digital as they become more integrated and NWS seems headed down the same path. Digital control systems provide a few unique capabilities. For example, an integrated control aircraft with battle damage could reconfigure the flight control system and the NWS controls to improve the chances of a safe landing. Multi-input and adaptive control systems may take into account such variables as air and ground speed, runway surface conditions, aircraft weight, and brake response. Digital systems also lend themselves to fault detection and test more easily than analog systems.

Concerns for digital systems include component reliability problems resulting from the harsh aircraft environment. An additional concern is software costs which caused problems in past aircraft digital control systems.

Development of Steer-by-Wire Systems

Hydro-mechanical systems

Following World War II, NWS was either mechanical or hydro-mechancial. As shown in Figure 1, a hydro-mechanical system consists of a spool valve controlling a hydraulic actuator. Numerous variations in the hydraulic and mechanical linkages have been used, however most follow the functions shown in Figure 2.

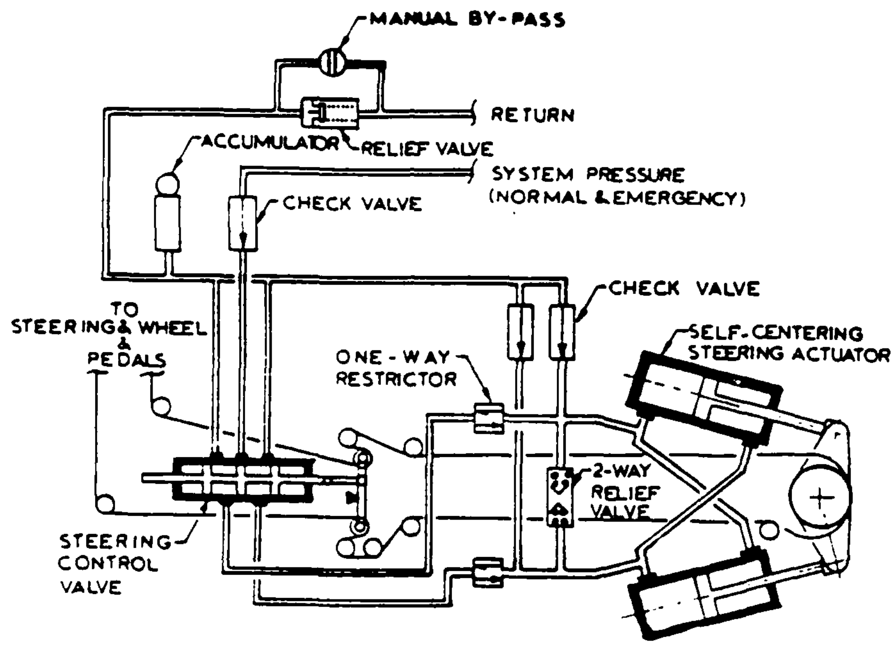

Figure 1. Typical hydro-mechanical steering system (Currey, 1984:11-5)

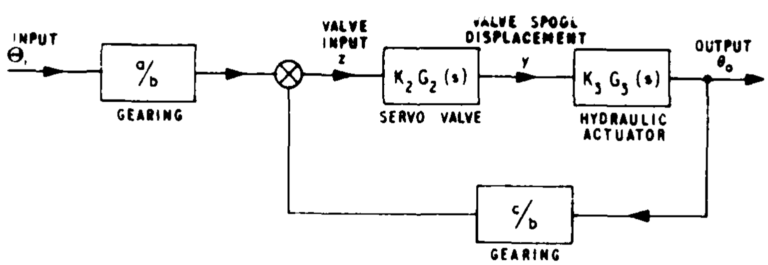

Figure 2. Typical steering functional flow (Walters, 1967:67)

Electro-hydraulic Systems

To decrease weight, electro-hydraulic systems have been used for NWS. Initial applications of these steer-by-wire systems were on military aircraft such as the F-4. More recently, civilian aircraft such as the Airbus A320 have begun using steer-by-wire systems. Such a system is comparable to fly-by-wire flight control. This adds two sensors, electric valve actuation, and control electronics to the basic hydro-mechanical system. One sensor (the feedback sensor) monitors the actuator position and physically resides on the nose wheel strut. The second sensor, referred to as the command sensor, monitors the rudder pedals or the steering wheel if used. In situations where the aircraft is fly-by-wire, the flight control rudder pedal sensors may be used. An electrically actuated spool valve controls the hydraulic fluid and is located close to the actuator. Figure 3 shows a typical system.

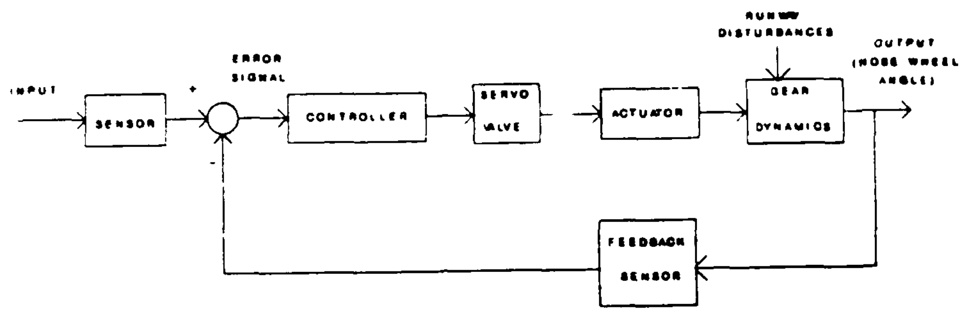

Figure 3. Electro-hydraulic steering system

Historically, the feedback sensor and connectors are prone to shorts and breaks. The resulting full-on or full-off signal can send the nosewheel to its stops (a hardover failure). Failure of the control electronics can likewise cause steering problems or simply shut the NWS down.

The increase in the number of components in an electro-hydraulic system over a hydro-mechanical system hinders efforts to improve reliability and maintainability. While steer-by-wire systems are designed with fault detection circuitry to avoid dangerous failures, such failures have occured. The F-16 is a good example of this. In December 1985 and January 1986, four F-16s experienced hardover NWS failures. Three were the result of solder joint connector failures and one was the result of failed electrical connectors which were damaged during maintenance. Later improvements in the circuitry greatly decreased the frequency of failures (FitzHarris, 1986).

Frequently, a redundant electrical sensing and control system is used to counter the higher component failure rates. The end result is overall system and mission reliability on par with mechanical systems. Figure 4 shows such a system.(Young and Ohly, 1985:8; Vander Velde, 1990)

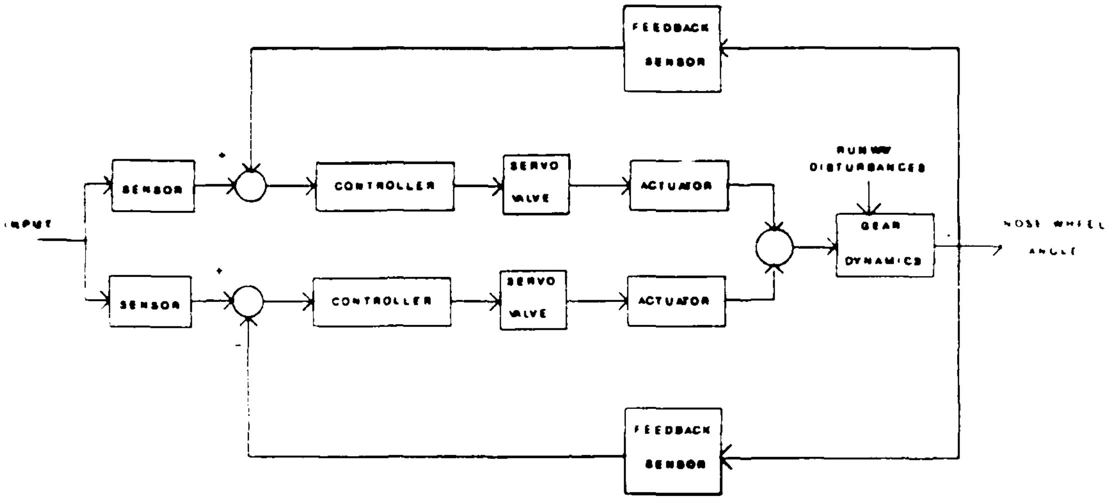

Figure 4. Electro-hydraulic steering system with a redundant control system

Digital Systems

A digital NWS system is simply a variation of the electro-mechanical system. It adds a digital-to-analog converter to the basic electro-hydraulic system and replaces the analog control electronics with a digital computer. The NWS control computer may be part of the aircraft central computer or a separate component. The analog-to-digital converters may be eliminated if the sensors provide digital signals directly (Young and Ohly, 1985:13; Belmont, 1985:8-11; Jenney and Schreadley, 1984). Figure 5 shows a typical digital NWS system.

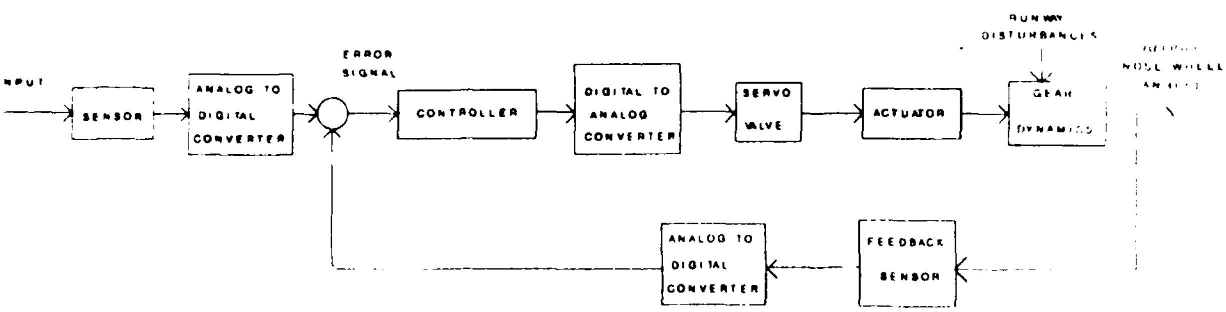

Figure 5. Digital steering system

Integrated Aircraft Brake Control Systems

Current trends in aircraft control systems stress integration of related subsystems. The NWS system is no exception. To improve overall landing performance, the control systems for NWS, braking, aerodynamic surfaces, and propulsion are being integrated. Since the braking, flight, and engine controllers are likely to be digital the NWS controller is likely to be digital for integrated systems. The F-15 STOL and Maneuver Technology Demonstrator (S/MTD) is a good example of such a system (McDonnell Aircraft Corporation, 1989). New fighters such as the Saab Grippen and Dassault Rafale are planned with integrated brake control systems. Figure 6 shows a typical integrated aircraft brake control system controller.

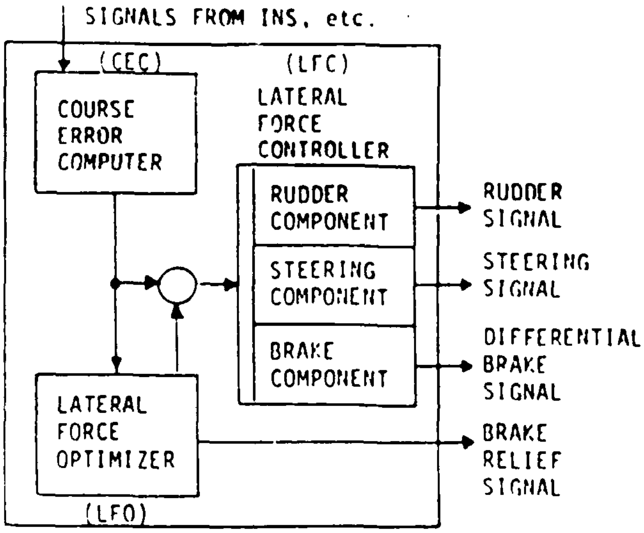

Figure 6. Integrated Aircraft Brake Control System (Smith and others, 1985:3)

Analog Controllers

Initial analog controllers were purely mechanical such as in hydro-mechanical NWS. The mathmatical theory for analysis and design was developed from the differential math used to describe the behavior of analog systems. Analog servo-electronics fit into this analysis and design capability directly. Compared to mechanics, electronics are comparatively easy to design and modify which enhanced the popularity of electronic controllers. The reliabilty of controllers was often less than for mechanical controllers. Over time, experience usign these components led to more reliable designs.

In many situations, an electrical controller is lighter than a mechanical equivalent. As a result, electrical controls were developed for aircraft. The F-16A is a good example of a fly-by-wire aircraft using analog electrical control. The more recent F-16C uses digital flight control for some of the reasons discussed in the next four sections.

Why Use Digital Control?

This section examines the benefits of digital control with some specific applications to NWS. This is approached by examining functional areas where digital systems can potentially perform better than an analog system.

Trends

Aircraft systems in general are making increased use of computer control. The hoped for benefits are improved upgrade capability, improved control performance, better system management, improved safety, lower costs, decreased weight, and better maintainability.

Digital control tasks may be roughly divided into three areas: (1) dynamic system control, (2) system supervision, and (3) system to system integration.

In its simplest form, dynamic system control using a digital computer may be viewed as replacing an analog controller with a computer (compare Figure 3 and Figure 5). Many early digital aircraft applications were applied to stand-alone systems of this type. An example of this is replacing an analog anti-skid controller with a digital one. More complex controllers may use multiple inputs and control multiple actuators. To control complexity, actuators and sensors are being developed that accept and generate digital signals directly, thus avoiding the need to convert between analog and digital signals (Belmont, 1985:8-11).

System supervision covers tasks such as monitoring power and controlling the sequencing of discrete events such as landing gear extension. This may often be thought of as logic or sequence control.

System-to-system integration is basically the communication of information between otherwise separate systems so that systems may coordinate their efforts. This may be simply passing system health information back and forth or may include swapping signals for dynamic system control. Vehicle Management Systems (VMS) and MIL-STD-1553 data busses are examples of systems that provide means for these integration functions.

Flexibility in Upgrade

One of the earliest rationales for using digital control was the ease with which a software resident digital control algorithm may be changed. For aircraft in the prototyping or test stage such flexibility is very useful. The F-15 S/MTD program made extensive use of this flexibility to tune controllers.

Upgrades of more mature systems also make use of software flexibility. Central flight control software on digitally controlled aircraft are routinely changed to add capabilities.

While this ability to make software changes eliminates most of the circuit changes required with hardwired analog control systems, testing and validation of any changes is still required. As with hardware, when software is changed, the system must be requalified as safe for flight. This is an involved process (Muenier, 1988). When subsystems communicate with each other, the interactions and hence the testing become more complex.

Adaptability

The ability to change a control law in real time in response to unknown variations in the environment or system is referred to as adaptive control. Such a controller can generally achieve better control over a wider range of variations than can fixed controllers. The tradeoff is the increased complexity required for adaptive algorithms. Some of the earliest adaptive control development was driven by the need to control aircraft under a wide range of conditions (Whitaker and others, 1958). Adaptive controllers are now again under consideration for aircraft flight control because of their ability to accomodate some types of aircraft failures (Ahmed-Zaid and others, 1990).

Adaptive control may be implemented with analog circuits. Such analog adaptive controllers have two shortcomings: (1) adaptive algorithms tend to be complex so analog circuits are cumbersome, and (2) analog circuits are prone to noise and drift in the multiplication and integration processes that adaptive algorithms require. If adaptive control is used, a digital controller is simpler and lighter.

Digital controllers cope with complex algorithms well. Multiplication and integration in a software algorithm is nearly noise free. These points are important when adaptive control is used for nonlinear systems such as NWS. Since the nonlinearities need to be incorporated into the controller, the adaptive algorithms become more complex (Goodwin and Sin, 1984:231-232).

Whether adaptive control is used for NWS depends on performance demands required from the system. Consideration must be given to conditions that influence NWS such as aircraft weight, runway friction, and crosswind speed. If the conditions are expected to vary widely and these conditions impact NWS controller requirements, then adaptive control may be appropriate. Current applications do not seem to fit these requirements however. Future systems which are highly integrated with other systems and are required to function in adverse conditions as discussed in the next section may require adaptive control. In that case, a digital system should be used.

Gain Scheduling

Control laws may be designed to vary based on some measurement of an external variable. While this is not considered as adaptive control, these adjustable controllers are useful for systems with known responses to known environmental changes. Aircraft flight controllers adjust to such things as air density and airspeed. Gain scheduling was initially used for aircraft flight control instead of adaptive control because gain scheduling requires less computation. In a slight variation of the gain scheduling controller, a variable structure controller was used on the F-15 S/MTD to accommodate five separate control laws to best meet different scenarios.

Concerns

Two basic concerns that arise with the use of digital control systems are bandwidth limitations and integration problems. These would lead a system designer to use analog components.

The speed, or bandwidth, of a digital control system is limited by the sampling frequency of the analog-to-digital converter passing signals to the computer and the computer processing capability. The sampling frequency must be at least five times faster than the control bandwidth. When the NWS controller is a separate computer, the sample rate may be easily selected. In cases where the NWS uses the central flight control computer, the sample rate will likely be determined by flight control requirements. Fortunately, sample rates required for flight control are generally fast enough to be sufficient for NWS. (see appendix A for details)

Flight critical systems, which include some NWS, require extensive safety validation and testing which includes software in the case of digital control systems. Current trends toward integration of aircraft systems via computer links greatly complicate the testing process. The failure modes become very difficult to determine. Current programs have large testing backlogs due to the test time required. For example, software changes in the F-16 can take up to a year to test. Even experimental programs such as the F-15 S/MTD had a difficult time maintaining their schedule during software changes (Clough 1989).

Performance

Whether performance is a player in the analog verses digital debate depends on what is expected from NWS. This section briefly reviews some NWS performance issues.

Integrated Control

High crosswind landings require NWS as part of an integrated brake control system. Such a system coordinates NWS, braking, and aerodynamic surfaces to maintain lateral stability (Smith and others, 1985; Warren, 1987).

Lateral stability during short field landings also benefits from NWS. Thrust reversing reduces rudder authority, leaving only NWS or braking for steering. Braking effectiveness in some cases may also be reduced by thrust reverser interference with the aerodynamic surfaces used to keep force on the wheels.

Brake Distance

When differential braking is used for directional control, overall brake capabilities are reduced. This is due to the fact that ~~requiring~~ differential force precludes maximum application of brakes on both sides. As a result, the total brake distance is increased. This may be a concern for short landings and rejected takeoffs.

When nose wheel braking is used (Boeing 737, Dassault Rafale) steering is required. Nose wheel friction forces may be used for braking, steering, or a combination of the two. To control the distribution of available friction, the nose wheel angle must be controlled. Even if the nose wheel is not required for steering the aircraft, effectiveness of the nose wheel brake is improved by controlling the nose wheel angle. If the angle becomes too great, even a small braking force will cause a skid. In an unsteered, braked nose wheel, any rotational deflection (for example due to a runway repair), will decrease the tire longitudinal force, making the onset of a skid more likely (Domandl, 1969). The alternatives are either reduce the applied brake pressure or control the nose wheel.

Tire and Brake Wear

Control systems are routinely optimized for selected performance criteria. It may be possible to optimize an integrated steering system to reduce tire and brake wear. Since turning is one of the largest sources of tire wear, coordinating the NWS and brakes during turns could reduce tire wear. The gains per tire would likely be small. However, the payoff over the life of an aircraft fleet may be large.

Such optimal control systems may be developed for both analog and digital controllers. These controllers tend to get complex when using multiple inputs and multiple outputs. In this case a digital controller will be advantageous.

In all of the above performance areas, when the control system becomes complex, a digital controller will minimize hardware complexity for a given performance level. The control system may become more complex if fault detection is added as discussed in the next section.

Passive Fault Detection

Improving the reliability of a control system is a major contributor to improving the safety of a critical system. System reliability in this case is not the same as component reliability since components may fail but the control system must be designed to avoid dangerous failures in spite of component failures. Fault detection is a key technology required to insure system reliability. By detecting a component fault, the control system may then either shut down or engage some backup system or configuration if required.

This section reviews passive techniques to detect faults. These are techniques that do not manipulate the system under observation but rather monitor the system as it is doing its usual functions.

Limited Hardware Monitoring

The easiest way to detect faults is to simply use a system to monitor selected signals. Any signal that falls outside of a preselected bound is assumed to be a failure. Voltage levels, signal continuity, frequency, and comparison of normally similar signals fall under this passive classification. This is the approach taken on the F-16 NWS.

The F-16 NWS fault detection incorporates signal continuity relays. When a failure causes an open circuit, the relay monitoring the signal shuts the system down. These are the K4 and K5 relays in Figure 7. This works well if each possible failure mode will affect a relay properly. Unanticipated failures such as shorting out a signal instead of losing it can fail to trigger the relays. Early F-16s had just such a problem with shorts in the feedback potentiometer which failed to trigger the fault detection relays (FitzHarris, 1986).

Error Point Monitoring

One currently used fault detection technique is to monitor the control system error point (error signal in Figure 3)(Young and Ohley, 1985:13; Folkesson, 1980:3-6). This approach is a subset of the limited hardware monitoring discussed above. Error point monitoring relies on the fact that the error signal is a measure of how well the output (steering angle) follows the input (pedal position). Some error magnitude limit is defined and any larger error signal is assumed to be the result of a NWS system failure. This approach tends to detect a larger variety of faults than the hardware monitoring approach. The F-16 incorporated an error monitor in the NWS (fail safe circuit in Figure 8).

Two problems may exist with this approach. The first is that the error may occasionally be large for short periods of time, even without a fault in the system. For example, on a NWS system with low stiffness, a bump induced nose wheel impulse can create a brief, large error in accordance with the natural system dynamics. Similarly, in a slow moving system or one with nonminimum phase (Ogata, 1970: 345, 459), a sudden input change from the pilot will not be followed immediately by the nosewheel position, creating a large error signal. A time delay in the fault detection trigger may cure this false alarm problem, but the delay may be dangerous in cases where an actual failure exists. This timing dilemma is common to many fault detection schemes that rely on a signal level trigger to detect a failure (Folkesson, 1980:3-9; Ogata, 1970:240, 459).

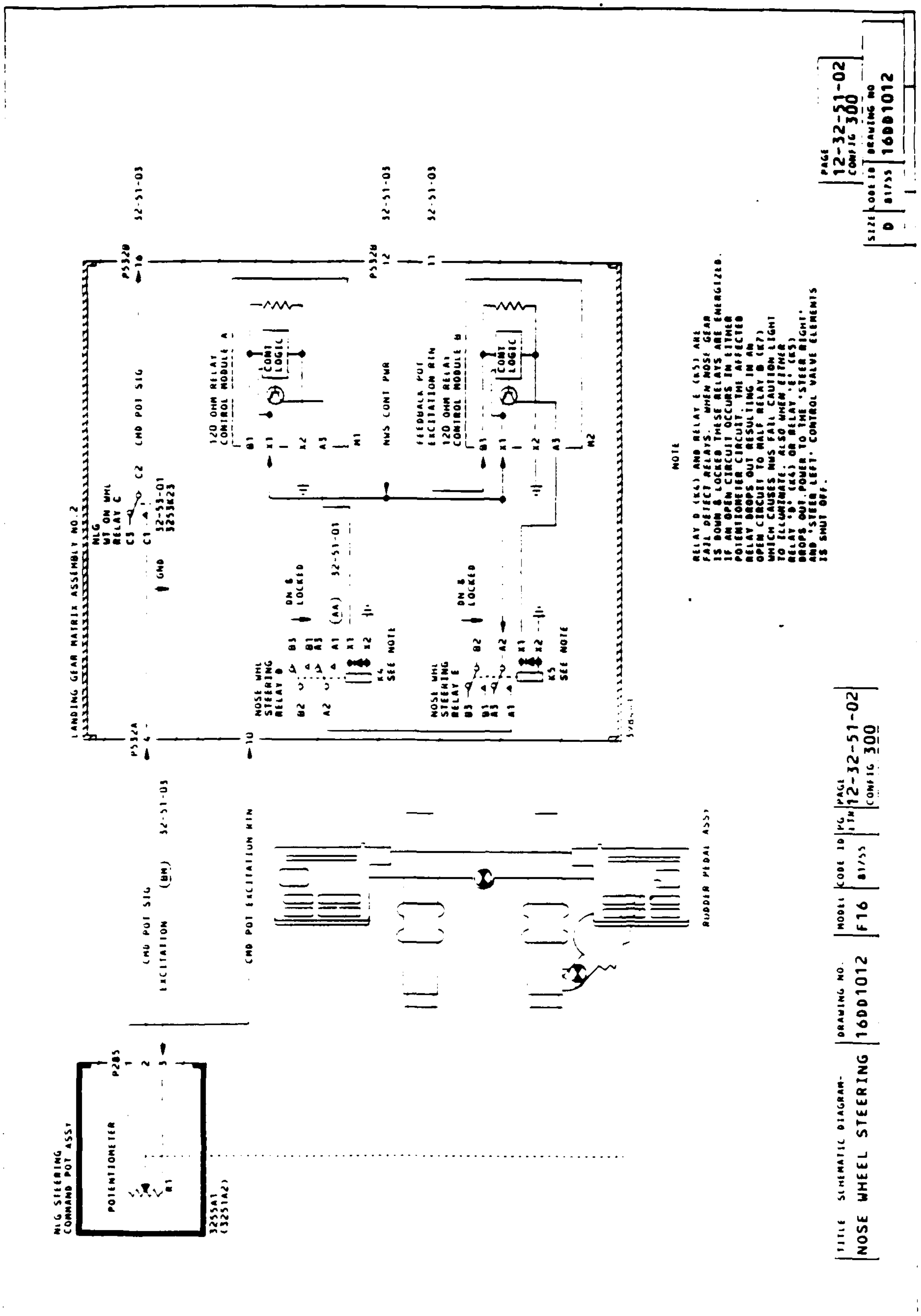

Figure 7. F-16C Nose Wheel Steering Command Schematic (Department of the Air Force, 1989)

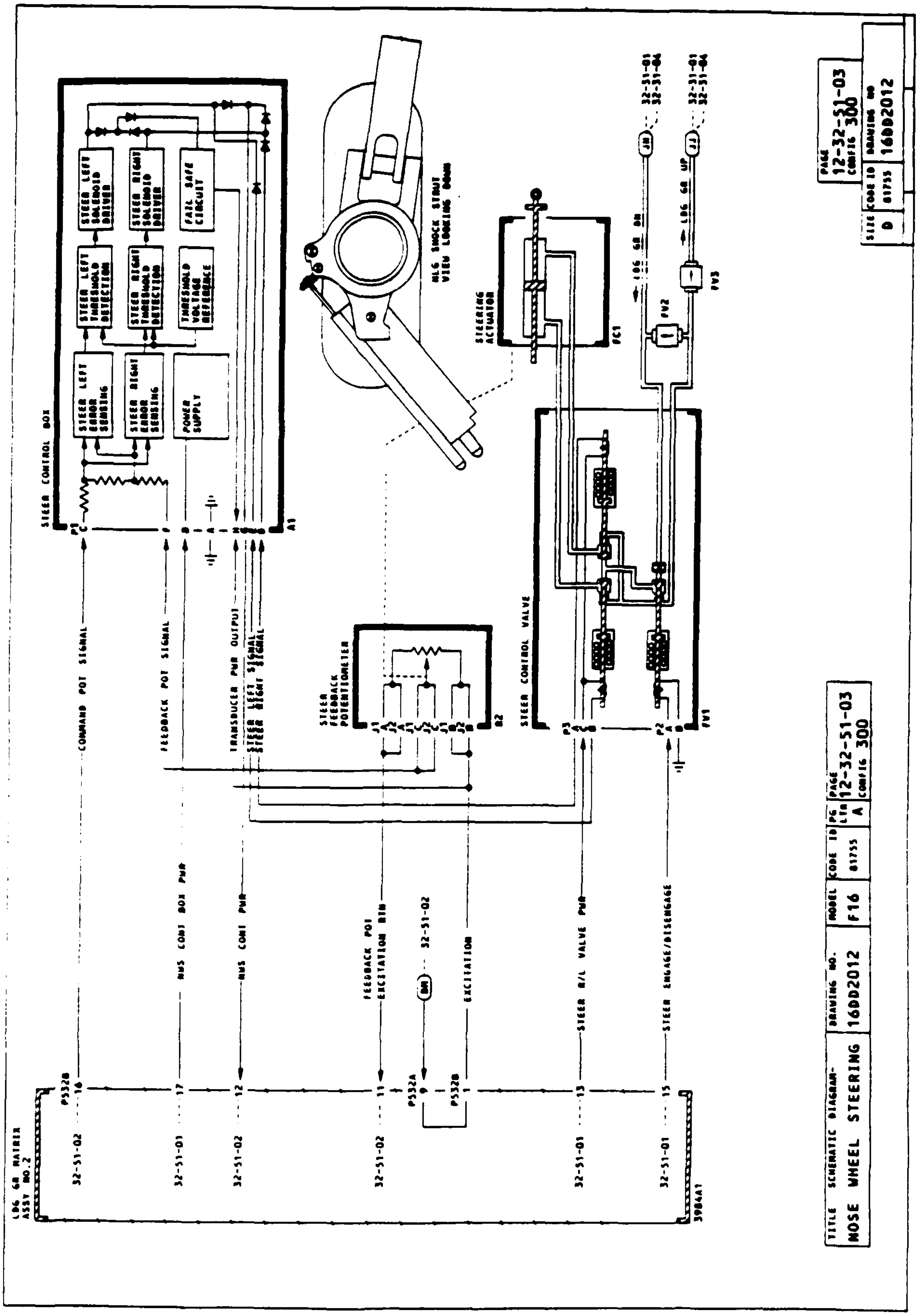

Figure 8. F-16D Nose Wheel Steering Actuation
(Department of the Air Force, 1989)

Another shortcoming is much more serious. Error point monitoring assumes signals from the command and feedback sensors are correct. A sensor or sensor connector failure could cause the nose wheel to fail hard over while the error signal stays within allowable limits.

Designs using the passive monitoring approaches rely on an accurate failure modes effects analysis (FMEA). Oversights in the FMEA can lead to failure modes that are not monitored properly. Fortunately, other approaches are available which are much less dependent on the FMEA.

Parallel Systems

A third fault detection technique relies on parallel NWS systems. The drawback is the weight of a second system. On the positive side, the likelihood of detecting a failure is near 100 percent (Folkesson, 1980:3-7). A parallel control system is required in general to achieve a probability of a system failure (vs. a component failure) less than 10^{-3} per flight hour. It should be noted that a parallel system adds to the component count, thus increasing the likelihood of a component failure.

When using the parallel or dual system approach for NWS, weight is controlled somewhat by using only partially parallel systems. In this case, the plant (control valve and actuator) is not duplicated but the remainder (the controller portion) is. One example is the De Havilland DH4 which has two parallel systems. The second system serves merely as a truth check to the primary system. Any disagreement between the systems indicates a failure and turns the NWS off.

While detecting the fault is easy, how does the fault detector know which system actually has the fault? To do so, each system must be separately monitored for reasonableness. For example, signal continuities and the error points of both systems can be monitored. Unfortunately, this is not fool proof. For example, if neither error is out of range, a sensor has likely failed. Determining which sensor failed is very difficult. Such a failure is said to be detectable but not distinguishable.

If a third parallel system is used, a single failure is not only easily detected, but the particular system with the failure is easily distinguished. What is required is a voting system such that when two systems agree, the third must be the failed system. Such systems are fairly robust in that they detect and distinguish a failure regardless of the specific component that failed. One of the motivators for quad redundant flight control is to ensure such triple redundancy even after one system fails.

Since such redundancy begins to add weight, the designer may begin to question whether such redundancy is worth the weight penalty for a NWS system. If passive fault detection is used for NWS, a triple redundant system should be sufficient to ensure proper operation.

Active Fault Detection

A fault detection system may manipulate the monitored system to detect faults.

Built-in-Test

The usual implementation of active fault detection consists of sending command signals to various points in the system. Output signals are monitored to see if they indicate a properly functioning system. Such capability is often referred to as built-in-test (BIT).

It should be noted that NWS system failures often exist prior to using the system. Consequently, built-in-test can troubleshoot prior to system use. This approach is used in the Panavia Tornado, in addition to using parallel systems. When the Tornado landing gear extends, the nose wheel is rotated through plus and minus 5 degrees to check out the system.

While more complex than passive systems, active systems provide more thorough fault detection. In a case such as the Tornado where NWS must function for safe landings with thrust reversing, the complexity may be justified. Active systems also have a good chance of detecting failure in nonredundant components. Generally, active fault detection is a complement to passive systems as opposed to a replacement (McGough and others, 1974:16-18, 222).

Digital Fault Detection

Fault isolation, system reconfiguration, and "graceful degradation" are concepts often associated with digital systems. Indeed digital systems are well suited to these tasks but it should be noted that anything discussed here can be done with an analog system. The tradeoff is the pain of complex analog circuits and the associated weight, difficult modifications, and reliability problems. This is contrasted with the inherent ease with which digital systems deal with the logic type operations associated with fault detection, isolation, and system reconfiguration.

A basic analog monitoring and test system can account for 20 to 30 percent of the control system weight. This weight includes extra interconnecting wires and connectors required for monitoring. Each wire and connector is a reliability problem in itself (Folkesson, 1980:16; McGough and others, 1974:93).

A complex fault check was included in the F-15 S/MTD flight computer. Fault detection software accounted for about 36 percent of the software code (McDonnell Aircraft Corporation, 1989:40). This has a much smaller impact on weight than comparable analog circuitry. Table I shows the flight controller load from a digital flight controller developed for the Saab Viggen.

TABLE I. Saab Viggen Computer Usage (Folkesson, 1980(2):20)

	Memory K-Words	In Flight Computational Load
Control Laws, Logic	2.8(36%)	40%
In Flight Monitoring	0.9(12%)	32%
Pre-flight BIT	1.7(22%)	NA
Executives and Utility	0.8(10%)	1%
Spare	1.5(20%)	27%

The digital system weight advantage is partly due to the sharing of the hardware between the control and fault detection functions. For example, after a preflight system test is run, the control program can displace the test program in the computer. Fault detection while the system is operating (i.e. passive detection) may be accomplished with a software module. Such detection requires only a very small increase if any in computer weight to provide extra computational and storage capacity over a comparable system without fault detection. Two approaches (among many) to digital system built-in-test are the use of a reference model and the use of component failure models to search for a fault.

The reference model approach is ideal for smaller controlled systems like NWS. A dynamic model of the system is written in software. Such a system is shown in Figure 9. The model is fed the same inputs as the actual plant. The results from the software model and the actual NWS are compared. This may be as simple as the error magnitude monitoring done with hardware systems. Discrepancies are assumed to be a NWS failure. It may also be much more involved, accounting for the impact of variables such as speed, weight, or runway condition. When an adaptive controller is used for NWS, a fairly detailed model will likely already exist. This appraoch is essentially using a parallel reference system like the De Havilland DH4, only without the weight and reliability problems associated with an actual parallel hardware system. This is often referred to as analytical redundancy.

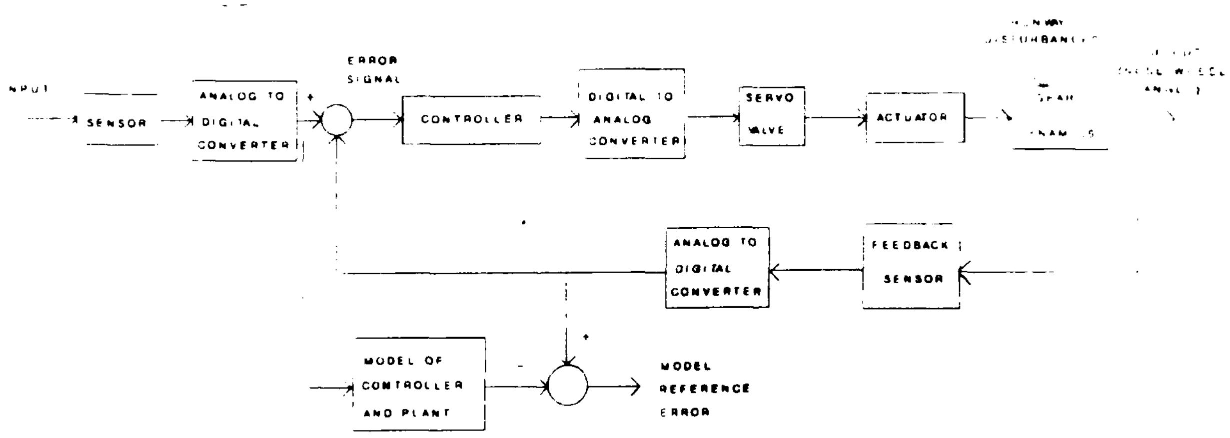

Figure 9. Reference Model Fault Detector

When hardware redundancy is already in place, the software model may still be used. In this case it is a third system providing a reference to the other two. A properly constructed model could identify which pieces of each hardware system have failed and, in the case of a sensor failure, could determine which sensor failed.

When the NWS fault detection software is in the central flight computer or when the NWS is connected to other systems with a bus or Vehicle Management System (VMS), information from other sensors will be readily available. Lateral motion accelerometers and yaw gyros provide aircraft directional information that can be used as a truth check to the NWS feedback signal by estimating the steering angle in the software model. In general, a properly designed estimator, using auxiliary sensors will provide a better estimate than a simple single input model (Maybeck, 1979:3-6). As components fail or environmental conditions change, the software model can also be designed to change or adapt appropriately.

Once the failure is detected, knowledge of the fault tree may be used to identify the specific component that failed. This information may now be used to isolate the failed component so as to limit the impact on the system performance.

Fault Isolation and Recovery

Two approaches exist to fault isolation: shutting the system down or switching to backup systems or configurations. Generally, shutting a system down reverts a NWS system to a free caster, called failing free. As discussed in the summary, this may be acceptable except when NWS is required for landing (high yaw landings, thrust reversing, nose wheel braking, or landing on damaged runways). The key to success is the time required to sense the fault and shut down the NWS system. Figure 10 shows a dual fail free system.

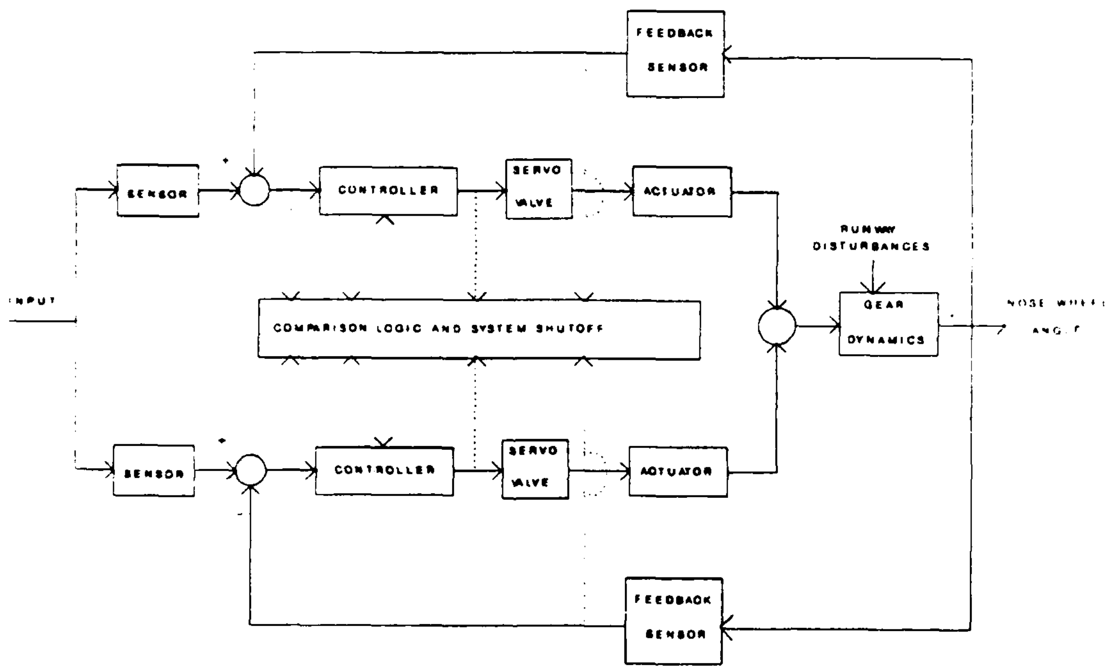

Figure 10. Dual Fail Free System

When a completely parallel NWS system exists, switching to the parallel system as a backup is straight forward. However, a complete parallel system rarely exists for NWS due to the weight of extra actuators. Fortunately, the availability of a complete parallel system is not always a necessary requirement for fault recovery. Generally, some form of NWS system reconfiguration is required. This roughly amounts to switching selected components to a backup instead of switching the entire system.

For weight control, usually only one hydraulic system is used but portions of the feedback and control electronics and sensors may be duplicated. If the sensed fault is a sensor failure, the second sensor may be switched in (recall that, in general, parallel sensors are required to discern a sensor failure). Ideally, either sensor should be switchable to either controller. The penalty to do this is an extra layer of management and switching components. Such a system is shown in Figure 11. The best reliability for a single channel on this sytem is $1x10^{-4}$ failures per flight hour whereas the system achieves $1x10^{-9}$ failures per flight hour.

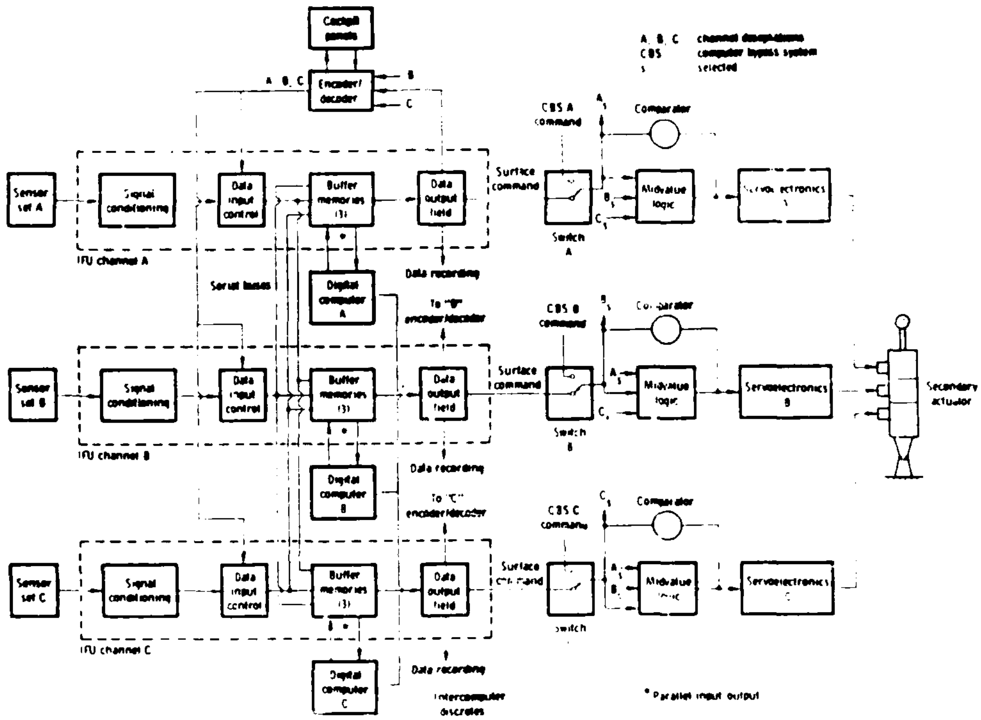

Figure 11. Triple Redundant Actuator Control With Switching. (Szalai and others, 1980: 8-17)

System Reconfiguration

Switching out failed components is just the sort of task a digital system is well suited for. The steps to follow when a failure occurs are easily programmed into a software algorithm. However, functioning hardware must still exist for such a reconfiguration to work. You cannot reconfigure to a parallel software reference model.

In the case where a parallel reference model is in software only, what can be done to keep the NWS functioning? The answer lies in the nature of the failure and the nature of the control system to be reconfigured. For example, if the feedback sensor fails, all may not be lost. The key is the existence of accelerometer and yaw gyro signals. A control loop may be closed around these to steer the aircraft. The bandwidth will be reduced but a pilot could still steer the aircraft (Figure 12). This assumes that the servo-valve is still stable. The space shuttle uses lateral accelerometers as the feedback sensors in this manner (Law, 1987).

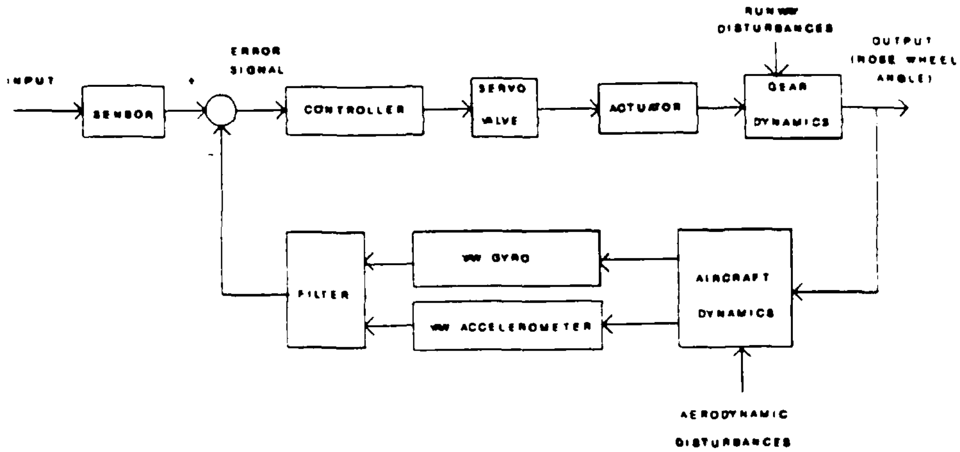

Figure 12. Gyro feedback steering

Even if the hydraulics or mechanical linkages fail, all may not be lost. This assumes the differential brake controllers are accessible to the control system. Computer controlled differential braking and use of the original nose wheel feedback sensor should provide some residual steering control (Figure 13). This is similar in concept to the current differential braking approach currently used by aircraft. The primary difference is the pilot would not have to worry about switching from steering to braking.

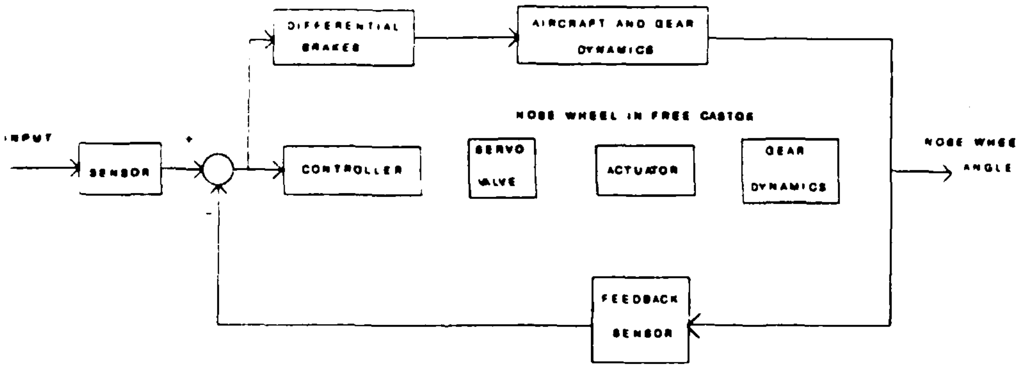

Figure 13. Steering with failed nose wheel hydraulics

Costs

NWS development and acquisition costs may be broken into actuator, sensor, and controller costs.

Actuators

Most actuators are driven by analog signals. On the surface, this appears to favor an analog control system. The output of a controller usually goes through signal amplification or conditioning circuitry prior to reaching the actuator. A digital-to-analog conversion step may be easily incorporated into this circuitry without adding much to the cost. In certain cases such as when the amplifier is pulse-width modulated, accepting a digital signal may even be simpler and less expensive.

Sensors

The costs for sensors in an analog or digital system are similar. Some cost savings may be realized by eliminating sensors. A minimum of two sensors is desirable for the nose wheel position feedback regardless of the controller. The command sensors may be eliminated if the flight control rudder pedal sensors are used. This tends to favor for NWS incorporated in a flight control computer or attached to a high speed flight data interface. With current trends to use digital systems in these areas, a digital NWS controller would be desirable.

A possible second approach to reducing sensor costs is based on use of poorer performing sensors. Sensors that are noisier or less precise are usually cheaper than better performing sensors. The approach to use these sensors consists of using an estimator to construct an approximation of a variable of interest, or state. This is done by combining information from several related sources.

In the case of NWS, the state would be the nose wheel angle. An inexpensive nose wheel angle sensor could be fed into an estimator along with signals from other sensors which are influenced by the nose wheel angle. These other sensors could be yaw gyros, lateral accelerometers, and main gear wheel speed sensors.

A digital estimator would be simpler than an analog one. If the extra sensor signals are already fed into the flight control computer, placing the nose wheel angle estimator there would be the least complex approach.

Controllers

The controller cost is influenced by the control law complexity. The complexity is a function of the desired redundancy and the desired performance. With analog controllers, the tie between control law complexity and cost is greatest. This is due to the number of discrete components being closely related to the control law complexity.

On the other hand, a digital controller has more costs that are fixed regardless of the control law complexity. For example the processor and memory can handle a wide variety of control laws. The primary digital costs that are complexity related are tied to the number of inputs and outputs to and from the controller. For example each additional analog input requires an additional analog-to-digital converter.

Incorporation of NWS into a centralized control computer shared with other functions is the least expensive digital option from the hardware perspective since it requires the fewest additional components. The potential catch is software development costs which can be very expensive. Software modification costs can be large if major changes are required late in the software development cycle. The larger the software is, the greater are the costs for documenting and testing changes.

By using a separate digital controller for NWS, the software costs may be reduced for cases where the NWS is not highly integrated with other functions and numerous changes are anticipated. Additional costs arise when the NWS is part of an integrated brake control system. In this case, and in cases with extensive reconfiguration capability, the software cost decrease realized by removing the NWS software will be countered by a large increase in the communication hardware and software.

Weight

Incorporating NWS into a centralized control computer is the lightest option. The weight increase due to adding NWS to a central computer is very small (Jackson, 1980).

Work is currently going on to develop direct digital sensors and actuators. These have the potential for eliminating the analog-digital conversions, further reducing weight and complexity.

On the F-16, removing the NWS input sensors and relying on the flight control rudder pedal sensors would save about two pounds. Removal of the steering control box would save about two pounds. This last weight savings, due to incorporating NWS in the central flight control computer, will be greater for more complex NWS control systems.

Maintainability

Removing control system complexity from hardware in an analog system to software in a digital one will have a positive impact on maintainability. On the hardware side of the digital controllers, using a separate controller will require more maintenance than when the NWS is in a central control computer.

Using parallel redundant control systems to insure system reliabilty degrades maintainability. The basic problem is the increase in the number of parts. A system with BIT could improve maintainability by providing details on part failures to maintenance personnel.

Summary

Table II summarises comparisons between analog and digital controllers. NWS performance is tied to the types as discussed in the report. The choice of digital verses analog requires consideration of a number of factors. Some of these factors are included in Table III found at the end of this summary. Table II is a summary comparison of analog and digital controllers for given types of NWS. Both tables are rated using a scale of unacceptable, poor, marginal, good, and very good.

TABLE II. NWS Comparisons for a Given Type of NWS

NWS Type	Analog	Digital
single	unacceptable	unacceptable
single with fault detection	poor	poor to marginal
dual redundant (fail safe)	very good	very good
dual redundant (fail operational)	marginal	marginal to good
triple/quad redundant		
-simple voting	good	good to very good
-BIT, reconfigurable	poor	good
Integrated brake control system	marginal	good

The analysis of whether digital NWS is an asset or liability requires consideration of many factors. Primarily, the NWS design is driven by operating requirements.

The first possible requirement is that of safety. For a system to fail safe (ie turn off in the presence of a failure), two parallel systems are required. When this failure requirement is the only major requirement, the choice of digital verses analog is not clear cut.

For systems designed to fail operational, a digital system presents several advantages. First, built-in-test is less complex with digital systems. Second, reconfiguration is easier with digital systems. In these cases, the digital system is the lighter option for a given level of capability.

A second possible major requirement is performance. Lower performance requirements may be met with an independent NWS system which may only be required for taxi maneuvering. Higher performance requirements necessitate integrating NWS with other functions. When NWS is part of an integrated braking system, digital systems are preferable. The preferred approach is including NWS in a central control computer.

TABLE III. NWS Comparison Background

NWS type	complexity and maintainability: analog	complexity and maintainability: digital	weight: analog	weight: digital	system safety and system reliability: analog	system safety and system reliability: digital
single	vg	g	vg	g	u	u
single with fault detection	m	m	m	m	p	m
dual redundant (fail safe)	vg	vg	g	g	vg	vg
dual redundant (fail operational)	p	m	g	g vg*	m	g
triple/quad redundant -simple voting	g	m-g	m	m vg*	vg	vg
-BIT, reconfigurable	p	m	p	m g*	g	vg
integrated brake control system (with BIT)	p-m	m-g	p	m g*	g	vg

u: unacceptable
m: marginal
p: poor
g: good
vg: very good

* when in a central computer

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APPENDIX A

Sample Rates

Any digital control system has a rate (or rates) at which signals are sampled for digestion by the controlling computer. In a general sense, better performance is realized by faster sampling frequencies (f_s). Components working at a slower f_s are less expensive but their phase lag is increased. When a central aircraft computer is used for NWS, the NWS system designer may not be able to select f_s. For example the F-16 digital flight computer operates on data at 64 Hz and it would not be changed just to accommodate a NWS controller requirement for faster sampling. Fortunately, since NWS angular rates are low, the sampling rates in a central flight computer are sufficient. The following paragraphs discuss the frequency selection problem.

The classical lower bound for acceptable f_s is given by the Shannon sampling theorem which states that to reconstruct a signal, f_s must be at least twice the fastest frequency of interest in the signal. In a control system, the highest frequency of interest is usually the closed-loop crossover or cutoff frequency (see Ogata, 1970: 439). Frequencies above crossover are attenuated by the system dynamics.

Mechanical systems may have large resonances or modes above crossover that may be significant even with the natural system attenuation. Such modes at frequencies above the phase crossover are essentially experiencing positive feedback, a potential source of stability problems. These modes may also alias back into the control bandwidth, showing up there as noise. Thus, a control system rule of thumb selects f_s greater than four times the highest mode frequecy (Powell and Katz, 1975:975). A problem may arise if neither the modes nor the sample frequency can be easily changed. Can a lower f_s be tolerated?

The Shannon sampling theorem is based on some assumptions that are not necessarily applicable to digital control systems. Shannon assumes that the signal needs to be reconstructed which is not the case for digital control systems. Also assumed is infinite computational word size. Not addressed at all are effects of computational delays imposed on the control system by computer capability.

The control system performcance requirements may be examined to find alternate f_s bounds. Franklin and Powell develop lower f_s limits by examining 1) control system response (or tracking effectiveness), 2) regulator efficiency (or disturbance rejection), 3) sensitivity to plant changes, and 4) prefilter design (Franklin and Powell, 1980: 275). These areas all apply to digital nose wheel steering (DNWS) systems.

Measures of dynamic response such as overshoot, rise time, and damping are all influenced by f_s. Higher f_s yields smoother output from the digital to analog converter (DAC) and generally faster response. These are tracking effectiveness requirements in the frequency domain and include bandwidth requirements. The controlled system natural frequency is proportional to the sampling frequency.

The ability of a control system to reject unwanted disturbances is also an important measure. A common measure is the root mean square (rms) of the control system response to the disturbance. For random type disturbances, as the correlation time for the disturbances decreases, f_s must increase to maintain equivalent performance. The ideal limiting case is continuous control (an analog system). Disturbance rejection is also affected by closed-loop dynamics which the designer has some control over through the control system compensation (and f_s). Hirata and Powell show that f_s eight times greater than the closed loop bandwidth yields a 50 percent degradation in disturbance rejection as compared to a continuous system (Hirata and Powell, 1990).

In a nose wheel steering (NWS) system, the primary disturbances are measurement noise, tire vibration, shimmy, and impulse type disturbances from damaged runways. A damaged runway may severely tax disturbance rejection capability. Sensor noise may be reduced by careful hardware selection and design and is usually less expensive than increasing f_s.

Effects of modes above closed-loop crossover may be removed if their spectral characteristics are known beforehand. One popular means of doing this for digital control systems is to use an observer, or model of the actual plant. This essentially puts notch filters at the mode center frequencies. For observers with low gain (and hence lightly damped) the notch is very narrow. Consequently even small mismatches between the mode frequencies and notch frequencies severely impact performance and even stability. These requirements on f_s are not as severe as those for dynamic response.

High frequency signals are usually removed prior to being passed to the computer by a prefilter. This keeps any high frequency signals small, and hence aliasing effects are kept small. Unfortunately since the filter is essentially low pass, it adds phase lag to a system around the filter center frequency (where the filter begins to roll off). To avoid affecting the system with this phase lag, the filter center frequency must be 5 to 10 times greater than the closed-loop crossover frequency. Now if f_s is kept 5 to 10 times higher than the filter, f_s would be 25 to 100 times greater than the closed loop frequency. As a result, designers usually live with the phase lag induced by the prefilter to keep f_s reasonable. This leads to slightly more complex algorithms.

APPENDIX B

NWS Case Summaries

F-16

The following reviews the development of NWS on the F-16. Many of the issues raised in this paper were faced by the F-16 Program Office

The F-16 NWS system was adapted from the T-39 NWS system. This was expedient during prototype development. As implemented on the F-16 it is an analog nonredundant system and is used for lower speed taxi purposes only. Signal continuity was monitored to shut the system down to a free caster in the event of a NWS failure.

When the F-16 went into full-scale development, the T-39 derivative NWS was retained. This was in spite of the fact that the T-39 had problems with sensor failures and included a backup sensing system not found on the F-16 implementation. When one sensor failed the backup was immediately switched in.

Following a series of hardover failures, the NWS controller was redesigned. The failure detection was improved, but still retained the signal continuity approach. The feedback sensor at the nose wheel was modified to reduce the liklehood of a sensor failure.

Several proposals for upgrading the NWS have been considered since the controller redesign. Replacement of the feedback sensor and servo valve have also been suggested as part of a general upgrade. One proposal was for a stand alone digital NWS controller. Basically, the analog controller would be replaced by a new digital design. This led to a proposal to incorporate NWS in the flight control computer.

Placing the NWS in the flight computer would reduce aircraft weight by about four pounds, would have been more reliable, and would have provided better BIT. General Dynamics also proposed an integrated aircraft braking system, which would be easy to implement in this case. The cost of the controller conversion was prohibitive. A major cost and schedule driver was the software, specifically software testing.

C-17

The C-17 uses hydro-mechanical NWS. The decision seems to be based on a desire for good reliability using well understood technology. The projected probability of failure is $4.5x10^{-6}$ failures per flight hour.

European Systems

A good discussion of NWS on European aircraft is presented in Young and Ohley's <u>European Aircraft Steering Systems</u> (Young and Ohley, 1985).

The French Rafale uses steer-by-wire and nose wheel braking. Steering on the prototype is not integrated with braking and aerodynamic systems however plans call for an integrated braking system on production versions.

Space Shuttle

A tire failure during the landing of STS-51D led to a redesign of the shuttle NWS system. Ground steering at the time of STS-51D relied on differential braking and aerodynamic control using differential drag from split elevons and rudder. A nonredundent NWS system was provided as the backup. Two NWS modes were available. One mode used the shuttle general purpose computers. Lateral accelerometers were used as feedback sensors. In order to start up the nose wheel control system in this mode, the initial position is assumed to be 0° with respect to the shuttle conterline. STS-30 had problems with the main gear Weight On Wheels (WOW) sensor which delayed activation of the NWS system. The delay allowed the nose wheel to deviate from 0° during a free caster. When the system finally came on-line, the nose wheel experienced large transients.

The second mode was a direct hardwired analog system. In this mode, the pilot served as the feedback sensor. Failure analysis showed this mode was susceptable to hardover failures. Use of this mode on STS-9 revealed that it was too sensitive at high landing speeds.

The STS-51D landing occurred in a crosswind. The need for differential braking in addition to braking applied to slow the shuttle placed extra demands on the upwind brake. Additionally, by using the aerodynamic surfaces for directional control, these surfaces were less effective at slowing the shuttle, further taxing the brakes, especially the upwind brakes which eventually failed.

Later analysis revealed additional concerns. When the rudder is used for ground directional control, the shuttle rolls to the outside of the turn, stressing the outer gear heavily. Also, the shuttle has a negative angle of attack when all wheels are down. This greatly increases the wheel loadings for high speed landings which in turn greatly reduces the lateral force capabilities of the tires. Studies also revealed the drastically different shuttle response characteristics of a landing roll with and without the NWS operating.

Since NWS is one part of a larger landing system, the landing control improvements involved more than just the NWS system. The current shuttle fleet had a "wrap-around" retrofitted fix while the new shuttles and overhauls on current shuttles will add more improvements. Additionally, to improve design and analysis, tire models in the simulations were updated to better reflect high loading effects and consequences of tire failures.

The retrofit to the current fleet added NWS fault detection to allow for NWS as a primary control. To do this, triple redundant nose wheel angle sensors were added to provide a reference to check the command signal generated by the accelerometer feedback system. It should be noted that the feed forward portion of the NWS system still has no redundancy. The analog manual system fault detection relies on sensing signal continuity and out of range signals. The control gains were altered to reduce the oversensitive response characteristics. The revised general purpose computer mode checks the variation between the accelerometer postion indication and the angular sensors as well as checking the rate at which the difference is changing. After a failure, the system fails free.

The proposed future upgrades will improve WOW sensing by using wheel speed sensors as WOW switch backups. The manual mode will be removed and the general purpose computer mode will be made dual redundant. On failure of the first system, the second will automatically turn on. When the second fails, the nose wheel will fail to a free caster. Additionally, a drag chute will be added.