SAE INTERNATIONAL

AEROSPACE RECOMMENDED PRACTICE

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Superseding ARP5007

Development Process - Aerospace Fly-By-Wire Actuation System

RATIONALE

ARP5007A has been reaffirmed to comply with the SAE five-year review policy.

FOREWORD

This SAE Aerospace Recommended Practice (ARP) is the direct result of technical contributions by a number of industry experts associated with SAE Committee A-6. It provides a structured process to assist in the successful development of fly-by-wire actuation systems for aerospace vehicles. The document's primary emphasis is on military aerospace vehicles; reflecting the technical contributions of committee members. Commercial aircraft programs require a similar process for the design, development and aircraft certification. This document can be readily applied to development of commercial aircraft actuation systems. However the commercial acquisition processes are unique and the major milestones are focused on enabling the aircraft to be introduced into in-service use.

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1. SCOPE:

This document provides a description of a process for development of fly-by-wire actuation systems. Included are (1) the development of requirements for the servo-actuator hardware and the electronics hardware and software, (2) actuator and servo-electronics interface definitions and, (3) the required communications and interactions between the servo-actuator and the servo-electronics designers.

1.1 Purpose:

This document provides guidelines and recommendations to assist in the successful development of fly-by-wire actuation systems for aerospace vehicles. The development process is divided into discrete phases by significant milestones or events which require completion of specific tasks. This document provides critical event checklists for use as evidence of completion for each milestone event. This document is primarily written for military aerospace vehicles. However, the development process can be readily adapted for the commercial aircraft actuation systems.

2. REFERENCES:

2.1 Applicable Documents:

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

AIR4094 Aircraft Flight Control System Descriptions

AIR4383 Description of Actuation Systems for Fly-By-Wire Flight Control Systems

AIR4922 Primary Flight Control Hydraulic Actuation System Interface Definition

ARP4386 Terminology and Definitions for Aerospace Fluid Power, Actuation and Control Technologies

2.2 Definitions:

The primary source for terms and definitions has been from ARP4386.

2.2.1 Abbreviations:

ATP	Acceptance Test Procedure
CDR	Critical Design Review
CE&D	Concept Exploration and Definition
DDV	Direct Drive Servovalve
DEM	VAL Demonstration and Validation
DOD	Department of Defense
EHA	Electrohydrostatic Actuator
EHSV	Electrohydraulic Servovalve
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
E&MD	Engineering and Manufacturing Development
ICD	Interface Control Document
LVDT	Linear Variable Differential Transformer
PDR	Preliminary Design Review
RVDT	Rotary Variable Differential Transformer
SCD	Specification Control Document
SDR	System Design Review
SRR	System Requirements Review
TRR	Test Readiness Review
VMS	Vehicle Management System

3. SYSTEM DEVELOPMENT PHASES:

The DOD acquisition procedures for development of an aerospace vehicle divide a program into three major phases: Concept Exploration and Definition (CE&D), Demonstration and Validation (DEM VAL), and Engineering and Manufacturing Development (E&MD). The System Development Plan in Figure 1 shows the phases and milestones from statement of need to production go ahead. The schedule duration of these phases may vary depending on specific contract requirements. This document defines an actuation system development process that includes these major program phases. The primary purpose of the CE&D and DEM VAL phases is to establish system requirements and is presented for reference only.

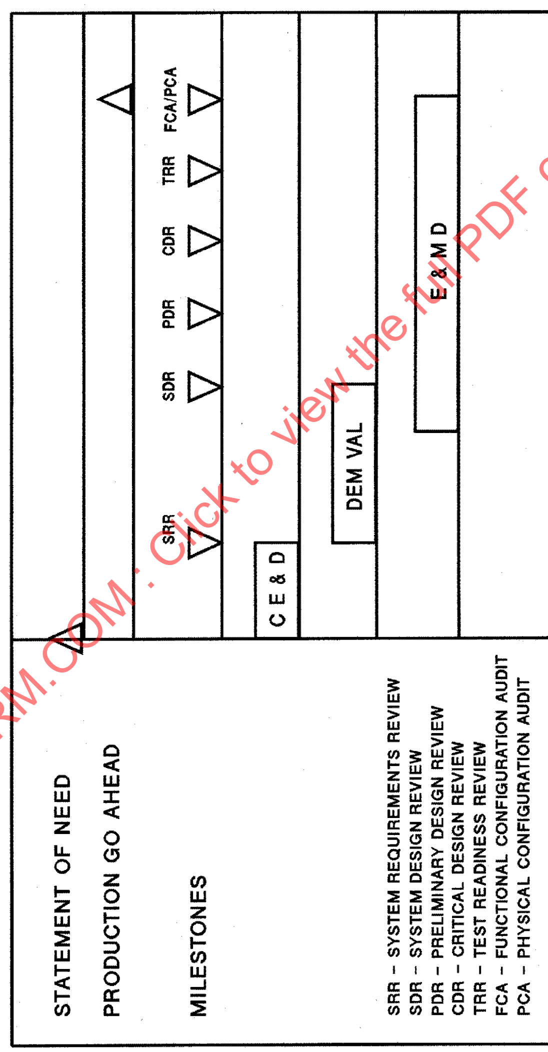

FIGURE 1 - System Development
Phases and Milestones

3.1 Actuation System Development:

Many recent aerospace vehicles are designed with fly-by-wire systems. A simplified schematic for a typical fly-by-wire actuation system is shown in Figure 2. This schematic shows that the actuation system consists of two major subsystems, the servo-electronics and the servo-actuator. To assure that the performance requirements of the actuation system will be satisfied, the system requirements for the servo-electronics and the servo-actuator must be coordinated with the developers of both these subsystems. These subsystems could be developed by different suppliers or different groups within the same organization. The overall actuation system development process is shown in Figure 3. The system requirements analysis during CE&D and configuration development during DEM VAL define the overall architecture and subsystem interfaces. After the system design requirements have been defined, the servo-electronics development and the servo-actuator development can follow separate and parallel paths until the subsystem hardware is assembled and combined for integration testing . With the development of the subsystems following separate paths, the success of this process is dependent on establishing actuation system schedules and a procurement cycle that requires concurrent design reviews for the subsystems as shown in Figure 3. To assure a successful integration phase there must be regular communication and interaction between the design teams/groups responsible for each of the subsystems. The guidelines in this document provide recommended tasks which should be completed at each milestone and the deliverables that should be exchanged by the two subsystem design teams.

3.2 Development Responsibilities:

The process described in this document presumes that the aerospace vehicle prime contractor retains actuation system engineering responsibility and that the servo-actuator and servo-electronics are developed via separate contracts with specialized suppliers. The aerospace vehicle architecture can range from a system with centralized computers that are part of a Vehicle Management System (VMS) to systems with dedicated actuation servo-electronics such as "smart" actuators and "cabinet" modular electronics. These subsystems may be connected by an electrical or optical data bus. The actuation system can be procured as a complete system with teams of suppliers that may be led by an electronics supplier or an actuator supplier. However, one organization must be assigned overall system responsibility. These variations in architecture, system responsibility, and procurement practices may require some modification of the wording and definitions in this process. Regardless of the actuation system architecture and assignment of lead responsibility, the basic process in this document remains valid since engineers with different skills and backgrounds must work together and formally communicate with each other to insure that the system is integrally successful.

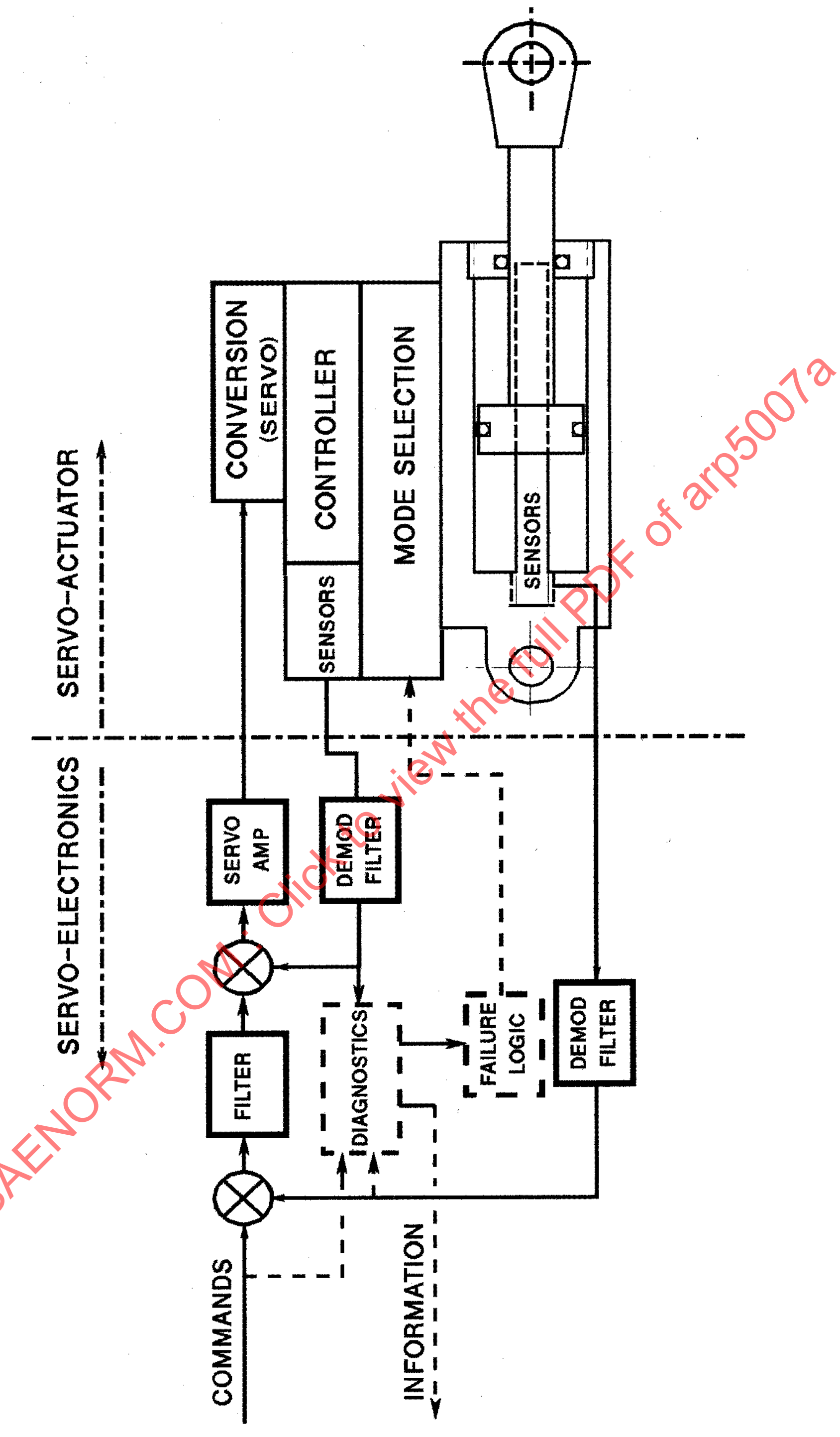

FIGURE 2 - Fly-By-Wire Actuation System

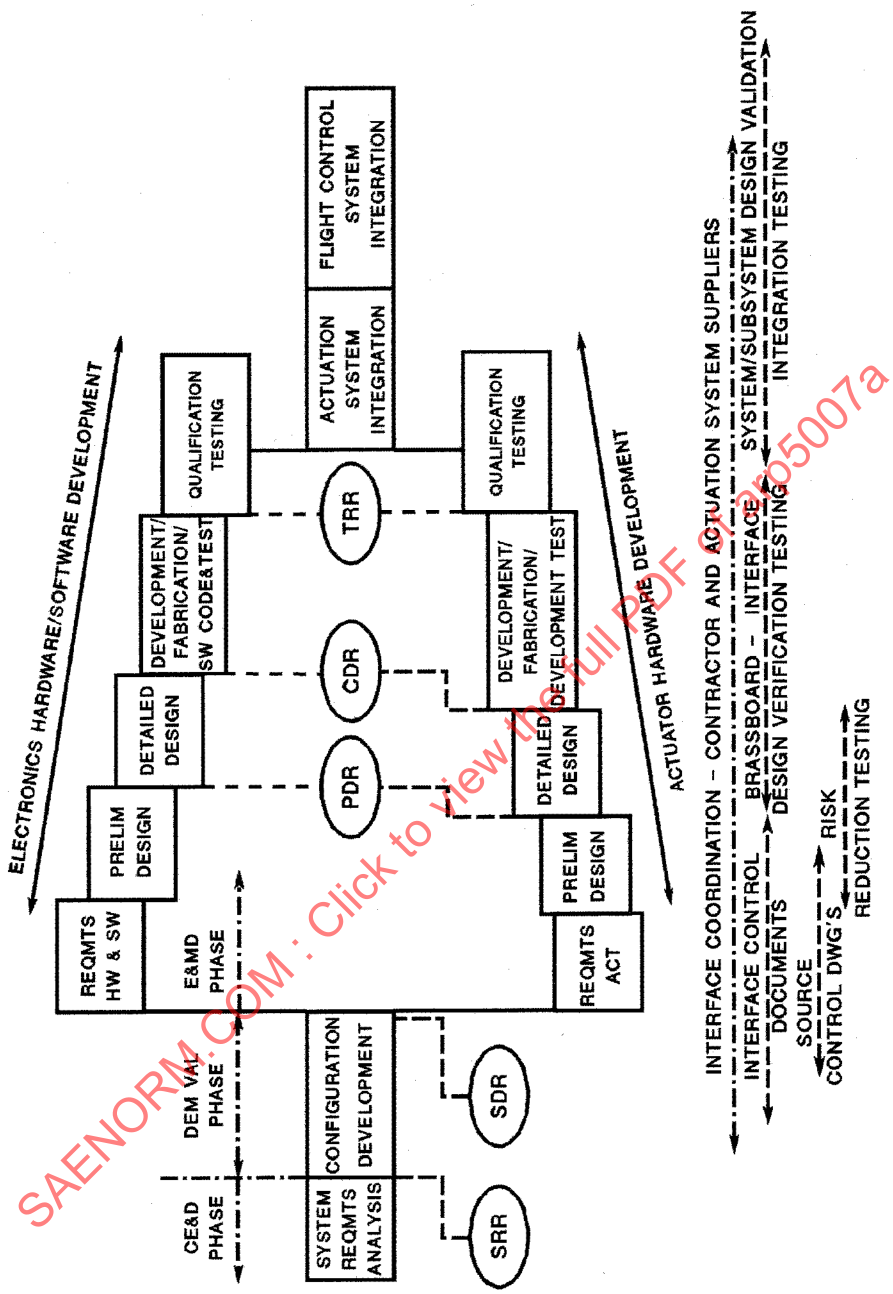

FIGURE 3 - Fly-By-Wire Actuation System Development

4. SYSTEM REQUIREMENTS ANALYSIS:

A system requirements review (SRR) is normally conducted during the CE&D phase of an aerospace vehicle's development process. The objectives of the CE&D phase are to: (a) define the most promising system concepts, (b) develop supporting analysis and data to identify high-risk areas and risk-reduction approaches, and (c) finalize system design requirements. The expected results of this phase of a program are top level design concepts for each of the vehicle's major subsystems, such as flight controls. These top level concepts are the baseline for trade studies which will be conducted in the DEM VAL phase of the vehicle's development acquisition process.

4.1 System Configuration Development:

A system design review is normally conducted as the final phase of the DEM VAL phase of the aerospace vehicle's development process. The objectives of the DEM VAL phase are to: (a) define the critical characteristics and expected capabilities of the system concept, (b) demonstrate that the required technologies can be incorporated into the design, and (c) establish a baseline definition for the most promising design approach. The expected results of flight control system design studies are:

System Safety Assessment

Vehicle Electronics Architecture
- Redundancy and back-up/degraded modes
- Distributed or centralized system
- Digital, analog, etc.

Preliminary Interface Requirements
- Servo-electronics loop architecture
- Failure detection and isolation
- Failure transients
- Built-in-test

Primary Power Source Characteristics
- Hydraulic
- Electrical
- Pneumatic

Actuation System Types (Flight Critical Energy Transmission)
- Linear and rotary hydraulic
- Hydromechanical
- Electromechanical Actuators (EMA)
- Electrohydrostatic Actuators (EHA)

4.1 (Continued):

Servovalve

Servo Loop Stability
- Gain and phase margins
- Servoelastic filtering

Primary and Secondary Actuation System's Redundancy
- Electronics
- Hydraulic
- Electrical
- Mechanical

Vehicle Installation
- Geometry
- Rigging
- Stiffness (vehicle structure and actuator)

Preliminary Sizing of Actuation System Components
- Stroke
- Loads
- Surface deflection rates
- Envelope
- Weight

5. ELECTRONICS AND ACTUATOR REQUIREMENTS:

The definition of the requirements is the first process of the E&MD phase of a program development. The primary objective of the E&MD phase is to define and translate the most promising design into a stable, producible and cost effective design. The primary product of the requirements development process is the specification control document or procurement specification used to define the requirements of a subsystem in sufficient detail that definitive contracts can be issued to suppliers. There are three significant documents that should be created during this phase to define the requirements for an actuation system such as the system shown in Figure 2. These documents are: (a) the servo-electronics Specification Control Document (SCD) or procurement specification, (b) the servo-actuator SCD or procurement specification, and (c) the Interface Control Document (ICD) that defines and documents the interface functions and characteristics between the servo-actuator and the servo-electronics. The combination of these three documents, or equivalent documents defined by the contracting agency which present the same information, should define the overall actuation system requirements. The SCDs include certification/qualification test requirements and define any specific design assurance and integration testing needed. The following checklists help in assuring key items are covered in these documents.

5.1 Actuation System Performance Requirements Checklist:

Redundancy
- Electrical
- Electronic
- Hydraulic
- Mechanical
- Other

Frequency Response Characteristics (Bandpass/Loop Gain)

Stability (Loop Gain and Phase Margins)

Threshold

Hysteresis

Accuracy
- Null bias/shift
- Linearity
- Temperature coefficient

Maximum Allowable Uncommanded Motion

Control Surface Slew Rate

Control Surface Hinge Moment Characteristics

Force Fight (Redundant Systems)

Failure Detection

Degraded/Fail Safe Modes

Failure Transients

Ballistic Survivability

Service Life (Operating Hours/Duty Cycle)

Reliability Allocations

Stiffness

5.1 (Continued):

Built-In-Test

Test Points

5.2 Servo-Actuator Performance Requirements Checklist:

Electrical

Hydraulic
- Fluid type and operating pressures
- Proof and burst pressure and pressure impulse
- Supply and return pressure variations

Load Stroke (Output Force/Travel)

Load Response Time

Load Acceleration

Peak Power
Main ram velocity, including system line losses or differential pressure across the actuator at maximum rate

Heat Rejection and Thermal Environment

Vibration Environment

Fatigue Design Requirements

Stiffness Requirements (Flutter)

Servo Characteristics (Interface Critical Item)
- Travel
- Slew rate
- Output force and chip shear force
- Dynamic performance
- Electrical characteristics
- Maximum quiescent hydraulic leakage
- Null bias and null shift
- Linearity
- Threshold
- Hysteresis

5.2 (Continued):

Main Control Valve Characteristics
- Active travel and overtravel
- Flow characteristics
- Pressure gain
- Quiescent pressure and unbalance
- Maximum quiescent leakage
- Operating force and chip shear capability

Main Control Valve Position Sensor (Interface Critical)

Main Ram Position Sensor (Interface Critical)

Pressure Sensors, if required (Interface Critical)

Shutoff Valve Electrical Characteristics (Interface Critical)

Reversion to Fail-Safe Transient (Interface Critical)
- Shutoff valve dynamics
- Mode select valve

Ballistic Survivability

Hydraulic Schematic

Electrical Schematic

Vehicle Installation and Physical Characteristics
- Weight
- Mounting provisions and envelope
- Operating geometry

Structural Design
- Service life and life cycling
- Impulse cycling
- Bottoming cycling
- Dynamic stiffness (interface critical)
- Component cycling
- Shock
- Acceleration loads
- Limit/ultimate loads

Leakage Requirements

5.2 (Continued):

Failure Detection Requirements

Reliability Requirements

Maintainability Requirements

Materials, Parts, and Processes

Duty Cycle

Power Consumption/Allocation

5.3 Servo-Electronics Requirements Checklist:

System Management

Computer Architecture

Redundancy Management

Failure Mode Effects and Monitoring

Fault Detection

Fault Correction

Fault Monitor Status

Built-In-Test

Maintenance Diagnostics

Servoloop Characteristics
- Algorithms/control laws
- Iteration rates
- Resolution

Channel Tracking/Balancing

Initialization/Start Up

Hardware Requirements

5.3 (Continued):

Servoamplifier (Servovalve Driver)
- Bandwidth
- Range
- Resolution

Position Sensor
- Excitation (electrical, optical)
- Signal conditioning

Solenoid/Shutoff Valve Driver

Digital Processor
- Software development plan
- Software requirements
- Memory
- Speed (throughput)
- Instruction set

Input/Output (Signal and Power Polarity)

Electric Power

Bus Interface

Signal Interface

Electrical Wiring

Signal Conditioning and Compensation

Thermal Conditioning

Operational Environment (i.e., temperature, vibration, shock, EMI/EMC, etc.)

Growth Capability

Electronic Parts Selection

Interchangeability and Repairability

Materials, Parts and Processes

Lightning, Bonding, Static Electricity, and Personnel Shock

5.4 Interface Agreement Requirements:

Fly-By-Wire actuation systems require detailed Interface Control Documents (ICD) to ensure that the actuator and the servo-electronics can perform as a complete system. The ICD preparation requires the participation of at least three parties: (a) the system integrator (customer), (b) the servoelectronics supplier, and (c) the servo-actuator supplier. The responsibility for preparation of various sections of the ICD and a brief description of the contents of each section is shown in Table 1. An ICD contains information required to properly define the external interfaces and the interface between the servo-electronics and the servo-actuator. It typically includes but is not limited to the following:

Electrical Interfaces
- Loop closure gains, filtering, and limits
- Servo (DDV, EHSV, etc.)
- Shutoff valves
- Position sensors (LVDTs)
- Pressure transducers, etc.
- Electrical power sources
- Buses, wiring, connectors
- Power-up initialization

Hydraulic Interfaces
- Hydraulic system routing
- Mode select valve control
- Shutoff valve control
- Pressure transducer ranges
- Connectors

Mechanical Interfaces
- Actuator electrical and mechanical strokes
- Rigging requirements

5.4.1 Interface Control Document Format: The generic ICD sections listed below can be used to speed development, provide clarity, and reduce confusion when the product development teams start generating an ICD.

Top Level Functional Operation Description

Fault Monitoring Description/Built-In-Test

System Block Diagram
- System software functions
- Electrical hardware
- Actuator functions
- Subsystem boundary lines

TABLE 1 - ICD Contents Responsibilities

Paragraph	Description	Responsibility
Top Level Functional Description	Provide a top level description of the actuator's components and how they are controlled by the electronics.	System integrator with input from actuator and electronics suppliers.
System Block Diagram	Shows complete block diagram of all actuator functions and boundaries.	System integrator with input from actuator and electronics suppliers.
Loop Closure Block Diagram	Block diagram that shows all loop closure parameters including gains, filters, and limits.	Electronics supplier with input from actuator supplier and system integrator.
Software Control, Built-in-Test, and Fault Monitoring	Provides description of how BIT and Fault Monitoring logic operates and electrical interfaces required for proper operation.	Electronics supplier with guidance from the system integrator and input from actuator supplier.
Software Functions	Provides description of software functions such as failure description logic, failure disconnect logic, rate limiting, and actuator rigging.	Software developer (system integrator or electronics supplier).
Electronics Hardware Functions	Provides description of hardware functions such as electronics gains, current feedback, current driver maximum power output, LVDT excitation, command signal characteristics, etc.	Electronics supplier.
Actuator Component Detailed Definitions	Detailed requirements for servovalve motor coils, LVDTs, solenoids, switches, etc.	Actuator supplier.
Drive Circuit and Sensor Interface Definition	Detailed requirements for servovalves and solenoid driver circuits, sensor/ LVDT impedance loading interface.	Actuator supplier and electronics supplier.
Tolerance Analysis Block Diagram	Detailed description of component tolerances such as servovalves, control valves, sensors/LVDTs gain amplifiers, filter circuits, limiters, etc.	Electronics supplier and actuator supplier.
Wiring Interface Diagrams	Provides detailed wiring diagram including shielding, wire length and type, wire impedance, and pinouts.	System integrator with inputs from actuator supplier and electronics supplier.
Definition of Terms	Detailed description of terminology used between companies. For example, scale factor, range, polarity, and output stroke.	System integrator with inputs from actuator supplier and electronics supplier.

5.4.1 (Continued):

Loop Closure Block Diagram and Parameter Description

Component Detailed Parameter Definitions
- Servo (DDV, EHSV) motor coils
- Shutoff valves
- Position sensors
- Switches
- Etc.

Drive Circuit/Sensor Interface Definition

Tolerance Analysis Block Diagram

Wiring Interface Diagrams

Definition of Terms

6. PRELIMINARY DESIGN:

A Preliminary Design Review (PDR) is normally conducted at the conclusion of the preliminary design tasks. The purpose of this review is to: (1) evaluate the technical adequacy of the selected design approach, (2) determine its compatibility with performance and engineering specialty requirements, (3) assess technical risk associated with the manufacturing methods/processes, (4) establish compatibility of the physical and functional interfaces among the components within a subsystem and with other subsystems, and provide approval to continue the final design process, and (5) specific entrance and exit criteria required by the contracting agency.

6.1 Checklist of Items to be Reviewed at PDR:

Preliminary design synthesis
Trade-studies and design studies results
Functional flow, requirements allocation
Layout drawings
Environmental and thermal design
Preliminary parts list
Preliminary weight analysis
Risk mitigation items, i.e.; Mock-ups, breadboard, brassboard, or prototype hardware
Preliminary specifications for procured components or subsystems
Preliminary EMI compatibility
Preliminary reliability/maintainability analysis
Preliminary stress analysis
Development test schedule

6.1 (Continued):

ICD
Failure modes and effects
Data items required by contract

6.2 Checklist of PDR Integration Issues:

The actuation system development flow chart in Figure 3 shows that after the specification control documents are completed the suppliers of the servo-electronics and the servo-actuator operate somewhat independently developing their designs. To ensure that the desired system performance will be met when the subsystems are operating together, the suppliers should exchange data for key design issues and demonstrate coordination and cooperation at their PDRs.

6.2.1 Servo-Actuator Data to Servo-Electronics Supplier: The servo-actuator supplier should update the information in the interface agreement/ICD. The review should include the results of design studies, computer model simulation, test data from breadboard, brassboard, and/or prototype equipment relating to interface requirements defined in the ICD. Also, highlight any deviations in component parameters and tolerances to allow the servo-electronics supplier to evaluate these characteristics in the detail design.

6.2.2 Servo-Electronics Data to Servo-Actuator Supplier: This is essentially the other side of the two way discussion and review of the actuation system design status detailed in 6.2.1 and includes reviewing the electronics design for reserve capability to cope with specific deviations in parameters defined in specifications for actuator components such as servo and position sensors. This two way coordination is a critical part of the development process.

6.2.3 Interface Compatibility Testing Plans: During the preliminary and detailed design phases, risk reduction and design verification testing should be accomplished to verify the interfaces and determine predicted system performance of the preliminary design using brassboard or prototype servo-electronics and servo-actuator hardware. The plans for this testing should be reviewed with the suppliers at PDR.