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ACTIVE CONTROL SYSTEM TRENDS

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ABSTRACT

The Active Control Concepts which achieve the benefit of improved mission performance and lower cost generate the system trends. The system trends are towards improved dynamic performance, more integration and digital fly-by-wire mechanization. These system trends yield new analytical issues and implementation requirements:

- Higher bandwidth, more dynamic coupling, stochastic and deterministic inputs.
- Limited control power.
- Multiple control loops, more interaction, multiple and conflicting criteria.
- Reliability (safety-of-flight requirements) and low cost.

New tools and approaches have been or are being developed to address the new analytical and implementation issues:

- Quadratic Optimal Control
- Multiloop Frequency Response
- Digital System Analysis
- Large Scale Integration
- Microprocessor technology
- Digital Architecture
- Software technology

INTRODUCTION

Active control system trends are towards improved performance, more integration and digital fly-by-wire mechanization. Most active control concepts are well known and will be briefly noted. The benefits are better mission performance and lower cost. The active control concepts and benefits determine the system trends.

The new analytical issues result from the active control system trends. An active control system has a first order effect on aircraft performance. More aircraft and controller configurations must be analyzed. The control design problem is larger and more complex. The designer must consider higher bandwidths, more dynamic coupling, stochastic and deterministic disturbances and commands and limited control power. Simultaneous implementation of some active control concepts yields design problems with multiple sensors, multiple responses and multiple control loops with multiple and conflicting criteria.

New tools are needed to address these analytical issues. Better aircraft mathematical models are required. Other tools are classical and modern controller synthesis and analysis approaches (quadratic optimal control, multivariable frequency response and digital systems analysis).

New implementation needs also result from the active control system trends. The designer is confronted with safety-of-flight control system requirements. Control system cost becomes a crucial factor in achieving control configured vehicle cost benefit.

New approaches to meet the implementation requirements are digital mechanization, advances in architecture to use microprocessors and to achieve fault tolerance, large scale integration and software technology.

These topics will be discussed in subsequent sections:

- Active control concepts and benefits
- Control systems trends
- Analytical issues
- Analytical tools
- Implementation needs
- Implementation technology trends.

ACTIVE CONTROL CONCEPTS AND BENEFITS

Active control concepts are well known and have been studied either on paper or by flight test on several airplanes:

- Relaxed static stability (e.g. C-5A, F-8, F-16, JA-37)
- Ride Smoothing (XB-70, B-52, B-1, C-5A, YF-12, JA-37)
- Flight envelope limiting (F-101, F-104, F-8)
- Maneuver load relief (C-5A, B-52)
- Gust load relief (C-5A, B-52, YF-12)

- Structure mode damping (B-52, C-5A, YF-12)

- Flutter mode damping (B-52, YF-12)

- Flight path and attitude coupling (B-52 direct lift control, C-5A, Advanced Fighter Technology Integration Program, C-130 gunship).

Other concepts which are related to the propulsion system can be included in a list of active control concepts.

- Propulsion integration (TF-30 and Joint Technology Demonstrator Program)

- Flight Propulsion Coupling (YF-12 and Flight Propulsion Control Coupling Program)

A rather extensive data base is evolving for these concepts [1 - 8].

The benefit of active control is improved mission performance (payoff) and reduced cost. The measure of performance is dependent on the particular aircraft's mission. It could include payload and range in a transport type aircraft and flight envelope and maneuverability in a fighter aircraft. The cost is total system life cost in dollars. The goal is to maximize the ratio payoff to cost.

ACTIVE CONTROL SYSTEM TRENDS

Active control system trends fall into three cateogires:

- Performance

- Integration

- Mechanization

Improving system performance increases the difficulty of the design problem and can affect the implementation cost. The designer must consider wider bandwidths and more dynamic coupling like in structural and flutter mode suppression and ride quality control. He must design control systems for both stochastic and deterministic commands and disturbances like maneuver and gust load control. When we push control configured vehicle concepts to the limit the designer is generally faced with limited control power. This can generate a requirement for flight envelope limiting or be a design constraint during flight envelope limiting.

Integration is required to implement more than one CCV concept along with conventional autopilots and control and stability augmentation systems. It is also a result of trying to improve performance by implementing favourable coupling. Control system or mode integration presents the designer with multiple sensors, multiple responses and multiple control loops with more interaction between variables. It can also present the designer with a multiple and conflicting criteria. Examples of the integration trend are the B-52 CCV program, the YF-12 Cooperative Autopilot Propulsion Control System program and the TF-30 Integrated Propulsion Control System program.

The system mechanization trends are towards safety-of-flight requirements and fly-by-wire mechanization. Safety-of-flight requirements come from the performance requirements of some CCV concepts like relaxed static stability. The SR-71 is a specific example. Safety-of-flight will be a requirement if future aircraft are designed to rely on stress relief or mode stabilization for structure integrity. Fly-by-wire mechanizations reduce cost and improve performance. Fly-by-wire has been demonstrated on the F-4, F-8 and C-141.

The mechanization trends are towards digital implementation. This is caused by the cost projections of digital hardware. Production digital hardware is here today on the JA-37 digital flight control. It is coming soon on the Space Shuttle digital flight control and main engine control, and the Integrated Propulsion Control System Program. Cost is the primary factor in the digital versus analog tradeoff.

ACTIVE CONTROL ANALYTICAL ISSUES

The analytical issues resulting from the systems trends and active control concepts pose a more difficult design and specification problem for the buyer and supplier. Active control system directly affect aircraft performance. The control design engineer is also confronted with:

- higher bandwidths
- coupled dynamics
- stochastic and deterministic commands and disturbances
- limited control power
- multiple variables
- multiple and conflicting criteria
- increased interaction
- digital specifications
- extensive system tradeoffs.

The origin of most of these issues was discussed in the previous section.

Two additional issues are digital specifications and extensive system tradeoffs. When digital mechanization is a candidate it is necessary to select and specify digital variables:

- sample rate and multiple sample rates
- wordlength and multiple wordlength
- computational delay and multiple computational delay.

This is a new analysis and design problem. Extensive tradeoffs between active control and aircraft concepts and configurations are necessary to optimize the benefit. Both aircraft and controller design and analysis speed and cost are the issue.

ANALYTICAL METHODS

In order to achieve the potential benefits of active control technology we usually require accurate and relatively complete descriptions of the aircraft dynamics. More design iterations of these sophisticated configurations are usually required.

NASA and the Air Force are funding significant efforts to develop computer programs to generate the aerodynamic and structural models from the standpoint of the control system designers needs and also to develop the programs necessary to rapidly synthesize and analyze active control configurations.

In addition, technology can be developed which will make the control system relatively insensitive to modeling deficiencies and errors. This is important for both reliability and performance reasons.

Modern control technology modulation to the well developed classical techniques presently exist to aid the designer. These are in the areas of Optimal Control, Digital Control and Multiple Input/Output Control.

OPTIMAL CONTROL. Quadratic optimal control synthesis techniques makes it relatively easy to handle:

- multiple control inputs
- multiple sensor outputs
- multiple responses
- multiple criteria
- stochastic and deterministic commands and disturbances
- digital and analog mechanizations
- constant or time varying dynamics
- short and long mission segments.

These features were recognized back in the early sixties. Since then over 30 man-years of development have gone into making the quadratic optimal methodology a practical design tool at Honeywell [9-12], probably many times that effort have been carried on throughout the United States. These developments of the quadratic design methodology have been directed towards:

- lowering the design cost
- improving control system performance
- constraining the designs to simpler hardware
- automated modeling
- consideration of the data and model uncertainties.

Today the quadratic design methodology for controller synthesis is a design and analysis software package. It can be used to:

- configure control systems
- compute control laws
- evaluate control system performance
- perform extremely rapid tradeoffs between competing configurations and control laws.

The ultimate benefits of this design tool are:

- mission oriented performance
- lower design cost
- better performance or cheaper hardware
- controller designs for complex systems.

MULTIVARIABLE FREQUENCY DOMAIN. It is necessary to take a new look at the stability criteria when systems or CCV concepts are integrated and multiple control loop designs are implemented. Vector frequency response or multiple variable frequency response is a generalization of classical gain and phase stability margins. It is valid and meaningful for multiple loop systems [13-16]. This concept can be used to write specifications for integrated or coupled systems. It can also be used in the design process to achieve the specification or improve the design.

DIGITAL CONTROL. Digital implementation confronts the designer with a new problem - specifying digital variables. In the past, the analyst has designed control laws to meet performance specifications, the systems engineer has put together control modes and switching and the circuit engineer has designed the hardware. Interaction between these three functions was minimal. In a digital implementation the analysts control law performance is dependent on hardware variables (wordlength and computer speed) and system or software variables (sample rate and computational delay).

Designing digital control laws can be accomplished several ways:

- digitize analog design
- direct digital design (classical or optimal)

No matter what technique is used the issue remaining is what values of the digital variables are acceptable. The digital variables can be specified by digital analysis software. This software must compute performance and stability measures as a function of the digital system variables, i.e., sample rate, wordlength, computational delay or multiple values of these variables. The performance and stability measures include such things as pole and zero locations, gain and phase margins, rms and discrete responses and frequency response. Rapid analysis by this software can yield precise specifications [17].

Digital control also yields new capability like nonlinear control, adaptive control, long memory and tight tolerances. These new capabilities to date are largely unexploited.

IMPLEMENTATION NEEDS

The implementation needs that result from the active control system trends are increased system reliability, lower cost, and size and weight improvements:

- Increased system reliability - The safety of flight requirements of active controllers demand improvements in system reliability. This can be achieved through a combination of improved component reliability and through extensive and effective redundancy to achieve fault tolerance.

- Reduced cost - In order to realize the predicted improvements in performance it is important that implementation costs do not increase. Since the computational function required for active controllers are increased, the implementation cost per function must decrease.

- Size and weight improvements - Again the performance gains predicted through the use of active controllers can be maximized if the implementation size and weight of the controller can be reduced.

IMPLEMENTATION TECHNOLOGY TRENDS

There are a number of current developments and trends in digital system implementation technology that will contribute to satisfying the implementation needs discussed in the previous section. These trends and their anticipated impact are discussed below. This section deals exclusively with digital implementation technology since that is where the most significant gains can be expected.

LARGE SCALE INTEGRATED CIRCUITS. The availability of large scale integrated (LSI) circuits, in which hundreds of logic functions are implemented on a single chip, is allowing implementation of digital systems with improvements in both cost and reliability.

The major impact will be from standard (off the shelf) LSI which will be available in increasingly complex functional building blocks. In 1978, all of these will satisfy commercial specs, 25 percent will satisfy extended thermal specs, and 5 percent will satisfy mil specs. Some of these building blocks are:

- Memory modules - RAM's (Random Access Memories), ROM's (Read Only Memories), and EAROM's (Electrically Alterable ROM's) will be available at lower cost as the number of bits per chip increases. This not only impacts cost directly but it also allows more modular architecture to be used since small memories are economical.

- Programmable Logic Arrays - These are complex functional building blocks that are programmable to allow performance of a number of different logic functions.

- Microprocessors - LSI is making it possible to implement microcomputers at extremely low cost. More on microprocessor trends and their impact are discussed later in this section.

Custom LSI will also be available. In those cases where the function cannot be conveniently implemented with standard LSI, custom LSI can be justified for surprising low volumes. In reference 18 it is shown that for a volume of less than 100 systems, (the sample system consisted of 500 gates of random logic) it is cost effective now to use custom LSI as compared to standard Small Scale Integration/Medium Scale Integration (SSI/MSI) implementation. At a volume of 1000 systems, the cost advantage (including both recurring and non-recurring costs) is nearly an order of magnitude.

LSI, either standard or custom, or a combination of the two will provide major cost advantages now and increasingly so in the future.

The use of LSI implementation also provides advantages in terms of reliability, primarily because of a reduction both in the number of ICs and in the number of interconnects in the system. Reference 18 shows that in a typical digital subsystem of 500 gates of random logic, an order of magnitude reliability improvement can be realized with LSI implementation as compared to SSI/MSI implementation.

LSI implementation will also provide significant improvements in size and weight compared to the standard SSI/MSI implementation. The sample system of Reference 18 shows more than order of magnitude improvement.

MICROPROCESSOR TECHNOLOGY. The LSI technology has spawned a significant new technology called microprocessors. The microprocessor is defined as a standard programmable LSI which consists of a parallel arithmetic unit, a control unit, and a general purpose parallel data bus for memory and external device communications. This chip (or chip set) can be combined with LSI memory chips to realize a general purpose microcomputer for extremely low cost.

These microprocessors (commercial spec) are now being manufactured in high volume by semiconductor vendors. It is projected that by 1978, 200K instruction per second microprocessor chips (or chip sets) can be purchased for from $15 to $25 each in volumes of 100 or more. Thus 8 bit and 16 bit microcomputers can be implemented for as little as $200 to $400. While extended spec and mil spec microprocessors will undoubtedly cost more, they will be available.

These microcomputers, having the programmability of conventional general purpose computers, will be used in two ways:

- to perform computational functions
- to replace hard-wired logic

In both applications a significant fact is that there is no longer a driving force to use the device efficiently. System level cost trade-offs tend to lead to dedicated use of these devices for certain functions even though this may result in, for example, the device being kept busy only 20 percent of the time. This leads to important new trade-offs in the area of system architecture, which is discussed next.

ARCHITECTURE. By system architecture we mean the overall organization or configuration of the building blocks of the system. The significant trend here that will help satisfy the implementation needs of advanced flight control systems is a trend towards more distributed systems. From a digital computer point of view, this means networks of minicomputers or microcomputers rather than the uni-processor architecture. The low cost of the computer modules will lead to dedication of a computer module to a specific function rather than time-sharing or multi-programming to allow a computer module to handle several functions. This is done primarily to reduce software costs, particularly the executive program.

Extensive research and advanced development activity is going on now on distributed computer systems with emphasis on bussing techniques and executive techniques [19]. The distributed computer approach has the following potential payoffs:

- Cost - Since there is only one computer building block in the system.
- Expandability - Since the bussing and executive will allow a variable number of computer modules to be present.
- Fault tolerance - Techniques are needed to provide backup if a module performing a critical function should fail. Much more work is required in this area but since all computer modules are identical, it holds promise of being able to satisfy fault tolerance requirements without high levels of redundancy. The use of the small dedicated building block allows redundancy to be applied to varying degrees throughout the system depending on the criticality of the function being

performed. The interconnection mechanism is a critical resource in this system so special purpose hardware for fault tolerance may be required for it.

SOFTWARE. A trend towards using a library of software modules which can be tailored and linked to fit the software requirements of a specific system will have important impacts on both system cost and reliability. This is a significant change from current avionics software practice in which ad hoc techniques are used on a system by system basis, producing software that is both expensive and unique. Being able to select and tailor already validated modules to satisfy a new requirement also contributes to reliability because validation and verification of the software will tend to be more complete.

A trend towards the use of higher order languages is an important companion of the library of modules trend in order for the library to be transferable from one computer to another.

SUMMARY. The implementation needs of higher reliability and reduced costs appear to be achievable due to the following implementation technology trends:

- Large Scale Integrated Circuits can provide today order of magnitude advantages in cost, reliability, and size and weight compared to standard SSI implementations.
- Microprocessors are rapidly becoming available at extremely low costs. It is projected that 200K instruction per second microprocessor chip sets satisfying commercial specs will be available at $15 to $25 each.
- Distributed computer architecture consisting of a variable number of identical computer modules interconnected by busses are being developed. These architectures have potential advantages in hardware costs and in satisfying fault tolerance requirements.
- Software trends towards re-use of software through use of a library of modules will pay off in terms of both cost and reliability.

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