

OPPORTUNITIES FOR AIRCRAFT CONTROLS RESEARCH

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AIRCRAFT PROBLEMS THAT DRIVE CONTROL TECHNOLOGY

In the course of this discussion, I'd like to deal with what I consider to be four categories of aircraft problems which drive our technology. First are highly unstable vehicles that are emerging. Second, control technology is being driven by the current thrust and ultimate benefits that can be achieved by expanding the flutter boundary of combat aircraft. Third, we are witnessing, both in the fixed-wing and the rotary-wing world, a new emphasis on low-level penetration. This, as I'll discuss, will have some direct impacts on control technology. Fourth, in general, we along with other members of the avionics community have suffered some setbacks in our attempts to demonstrate "ilities" in the past. NASA and DoD have made great strides in this area; however, improved "ilities", if I can use the word as such, will continue to drive our control research technology.

- **HIGHLY UNSTABLE VEHICLES**
- **FLUTTER SPEED BOUNDARY EXPANSION**
- **LOW LEVEL AUTOMATED FLIGHT**
- **IMPROVED "ILITIES"**

CONTROL RESEARCH AREAS

Breaking down our discussions into technology research areas, I'd like to deal with control from a system theoretic standpoint, particularly multi-variable control theory and adaptive control. Many of the aircraft technology drivers I discussed earlier are going to affect what we do in the future of physical device research, particularly actuators, but also sensors, computers, and data transmissions. Some overall system concepts are going to be impacted by these directions, such as fault-tolerant architectures and some continued work required in the analytical fault-tolerant areas. This latter category is technology that we have pretty well in hand in our controls area, but other avionics system people really need the benefit of our experiences. Two other areas I'll just touch on basically are what control technology will have as an impact for future flight research and some comments on higher order language software.

SYSTEM THEORETIC

- MULTIVARIABLE CONTROL THEORY
- ADAPTIVE CONTROL

PHYSICAL/DEVICE RESEARCH

- ACTUATION
- SENSORS
- COMPUTERS
- DATA TRANSMISSION

SYSTEM CONCEPTS

- FAULT-TOLERANT ARCHITECTURES
- ANALYTICAL FAULT TOLERANCE

OTHERS

- FLIGHT RESEARCH
- HOL SOFTWARE

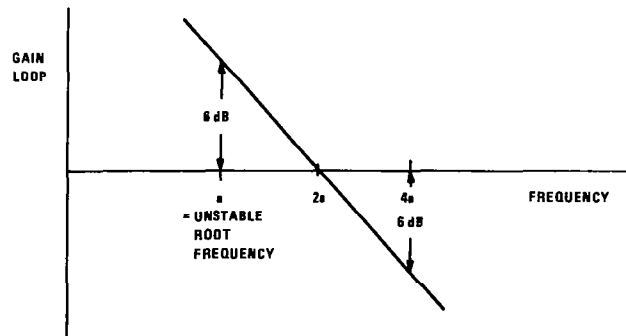
BANDWIDTH INCREASES DUE TO RELAYED STATIC STABILITY

Beginning with highly unstable aircraft, we may be witnessing a significant increase in bandwidth requirements for fighter aircraft, in particular due to the desire to achieve the benefits of low drag and maneuverability at supersonic speeds.

This chart shows a simple single-input/single-output Bode relationship. For instance, we can think of instability being measured by the magnitude of the root that is farthest to the right in the right half plane. If we denote that by the letter "a" in a frequency response plot, we'd like to be 6 dB in gain above this position as a rule of thumb. Another rule of thumb for control design engineers is that we'd like to be in the area of 20 dB per decade roll-off in the region of crossover. This simple relationship would then put the crossover frequency at $2a$. Likewise, for stability and robustness, we'd like to be at least 6 dB below zero gain at a frequency of $4a$.

Two examples of the loop requirements to stabilize the vehicle are the X-29 and the F-16. The only one that is in production is the F-16 fighter. Its worst flight condition in terms of stability contains a root at $+2$, which means our crossover frequency is at 4 radians per second, and we must be rolled off to the tune of 6 dB at 8 radians per second. However, if we look at the X-29 Forward Swept Wing fighter, we see that at its most unstable flight condition, it has a root at $+7$, which is approximately $3\frac{1}{2}$ times what the F-16 represents. This impacts our control bandwidth because we need a crossover at 14 radians per second, and we must be rolled off 6 dB at 28 radians per second.

Historically, flight control designers have had 6 dB to model systems that have the highest accuracy near crossover, i.e., $2a$ and $\pm a$ half of decade either side. In the case of the X-29 and potentially the emerging ATF class of fighters, this could easily mean that we need to know in greater detail the dynamics of the vehicle about $3\frac{1}{2}$ times higher in frequency than we've ever dealt with before. This would logically include more detailed knowledge of the bending/aeroelastic characteristics of the vehicle.



EXAMPLES:

F-16 FIGHTER

$a = 2 \text{ rad/sec}$
 \Rightarrow Crossover ($2a$) = 4 rad/sec
 \Rightarrow 6 dB DOWN ($4a$) = 8 rad/sec

X-29 FORWARD SWEPT WING

$a = 7 \text{ rad/sec}$
 \Rightarrow Crossover ($2a$) = 14 rad/sec
 \Rightarrow 6 dB DOWN ($4a$) = 28 rad/sec

FLIGHT RESEARCH

One of the initial impacts that high bandwidth control poses is in the area of flight research, and the goal as stated earlier is to achieve model uncertainty reduction in the vicinity of control bandpass. In the case of highly unstable vehicles, this means that we have to deal with higher and higher frequencies, and one of the ways we achieve model uncertainty reduction is through a series of flight examinations and parameter identification. The payoff, obviously, is to achieve an ultimate lowering of the eventual actuator rate excitations for high bandwidth control.

**GOAL → MODEL UNCERTAINTY REDUCTION IN
CONTROL PASSBAND**

**CHALLENGE → PARAMETER ID AT HIGHER
FREQUENCIES**

**PAYOFF → LOWER ACTUATOR RATE EXCITATIONS
FOR HIGH BANDWIDTH CONTROLS**

SENSORS

Let us look at how this nature of highly unstable vehicles impacts various hardware components. Historically, flight control sensors have had ample bandwidth. We at Honeywell feel that if more bandwidth is needed, then expansion is already feasible within the state of the art. Another issue that is cropping up here more and more is the notion of shared flight control/navigation/weapon delivery sensors. The placement issue is the one that we have to deal with in the flight control community, and the real goal here is to achieve a robust multivariable control for sensor fault tolerance and high bandwidth performance in the face of ill-placed and dispersed sensors. This technology development should continue.

- **FLIGHT CONTROL SENSORS – BANDWIDTH
EXPANSION FEASIBLE**
- **SHARED FLIGHT CONTROL/NAVIGATION/WEAPON
DELIVERY SENSORS**
 - **PLACEMENT ISSUES: ROBUST MVC FOR
SENSOR FAULT TOLERANCE
HIGH BANDWIDTH PERFORMANCE**

ACTUATION TECHNOLOGY

The next technology area relating to controls is in the area of actuators. We have three issues that we must deal with here.

The first issue is fault tolerance. There is an emerging class of technical developments dealing with digital servo electronics which will indeed make the actuators more fault tolerant. This is required, because if one looks at the reliability analysis of a current flight control system, we see that from a research standpoint we have been dealing effectively with computers and somewhat effectively with sensors, but the real reliability bottleneck in aircraft flight control is the actuator system.

The next issue is this bandwidth expansion that we've been discussing. Although I'm not an expert in actuator technology, I'll pose a couple of issues and concerns that I have. One concern is whether we have the hydraulic technology available to achieve the high authority and rate/bandwidth we need for unstable vehicles. I'll also note that electromechanical actuators are emerging, which might give us high authority and expanded rate and bandwidth. This technology development should be pursued.

Third, there is the rate expansion itself for highly unstable vehicles. One possible solution, within the system theoretic framework, is the capability to formalize an optimal blending, if you will, of multivariable control solutions which allows us to share the rate requirement among a number of different surfaces.

- **FAULT TOLERANCE**
 - DIGITAL SERVO ELECTRONICS
- **BANDWIDTH EXPANSION**
 - HYDRAULIC → COMPRESSIBILITY LIMITS
 - ELECTRO-MECHANICAL → EMERGING
- **RATE EXPANSION**
 - MVC SOLUTIONS FOR OPTIMUM BLENDING

COMPUTERS

Another important element in our control loop is the onboard digital flight computer. Computer technology is being driven by a number of different applications, flight control being one. For instance, throughput is really being driven by signal processing requirements on various aircraft and spacecraft applications. The word length related to the accuracy of the computations is being driven more by other avionics functions, such as navigation. Memory, likewise, is being driven by other functions also. Some of the storage requirements for digital landmass data, etc., come to mind.

One area that is currently being driven by flight control is fault tolerance. In the emerging set of research issues from a hardware standpoint, one needs to look at integrated-functions architectures such as integrated flight/navigation and integrated flight/propulsions.

Software on the other hand is being driven to higher order languages such as Ada. We have to be careful in the controls community not to accept massive, unreliable compilers that aren't necessary to do control work. One possible solution that is being explored by the software community is to allow defined subsets of higher order languages to be used by highly flight crucial functions like flight control.

In summary, control problems in general do not drive computer technology. Certainly the first three issues I've listed here are being driven by other requirements. Fault tolerance is currently being driven by flight control, but as we'll see when we get into the impact of low-level penetration, we will find that other avionics systems indeed need the same kind of fault tolerance that flight control currently does.

- THROUGHPUT → DRIVEN BY SIGNAL PROCESSING

- WORD LENGTH → DRIVEN BY NAVIGATION

- MEMORY → DRIVEN BY OTHER FUNCTIONS

- FAULT TOLERANCE

- HARDWARE: INTEGRATED FUNCTIONS
ARCHITECTURES

- SOFTWARE: HOL COMPILER SUBSETS

**BOTTOM LINE → CONTROL PROBLEMS DO NOT DRIVE
COMPUTER TECHNOLOGY**

MULTIVARIABLE CONTROL THEORY

I would like to comment on aircraft research problems that drive the control theoretical developments. Two areas I'll talk about are the actual basic mathematical theory itself and additionally how we might look at a research area for applying these techniques. First, in my discussion of unstable vehicles, I've alluded to uncertainty reductions and new regions in frequency that have yet to be dealt with. Likewise, in our development of mathematical theory, we have to formalize ways of dealing with uncertainties. For instance, if we can generate a mathematical description of uncertainty in a given frequency range, we should seek to formalize our control design problem to deal directly with that level of uncertainty. There is a body of research being conducted at Honeywell and other places actually dealing with what we call structured uncertainties.

The other side of the structured uncertainty issue is the design itself. One design technique we're looking at is direct frequency domain optimization that attempts to deal with a formalized approach to achieve performance goals in the face of uncertainty constraints.

Uncertainty representations for practical aircraft control design problems have not been developed beyond simple examples. Therefore, formalized uncertainty boundaries for practical examples should be examined.

The next item concerns the state of the art in analysis and design itself for the whole hierarchy of preliminary design to flight control development, to actual production of flight control systems. We in the control theoretic community have been remiss for decades in not providing the end-user, i.e., the guy who's actually going to design a flight control system, with the proper CAD tools to do his job. And even though we've taken a useful step back towards the frequency domain, the ultimate flight control designer will never use the tools if all he has is a published paper out of the Transactions on Automatic Control.

Third, more directly to the flight control problem itself, I alluded earlier to some sharing of surfaces to achieve some overall higher bandwidth goals. Coupling this idea with the proliferation of control effectors on board modern aircraft, one should look at ways to formalize the control law design. Once again, a driving goal is to achieve higher bandwidth control for highly unstable vehicles. In addition, emerging classes of work include the areas of integrated flight and propulsion control and also some rather higher risk areas dealing with robust reconfiguration of control surfaces in combat situations, which could have high payoffs.

- **DEVELOPMENT:**

- **STRUCTURED UNCERTAINTIES**
- **DIRECT FREQUENCY DOMAIN OPTIMIZATION**

- **APPLIED:**

- **FORMALIZED UNCERTAINTY BOUNDARIES**
- **ANALYSIS AND DESIGN TOOLS - CAD**
- **MULTIPLE EFFECTOR BLENDING FOR COMMON GOALS**
 - HIGHLY UNSTABLE VEHICLES**
 - INTEGRATED FLIGHT/PROPULSION**
 - ROBUST RECONFIGURATION**

ADAPTIVE CONTROL RESULTS

There have been some discussions about the usefulness of the adaptive control theory that has been developed over the last couple of decades. I'd like to go on record as saying that despite these emerging reservations, we at Honeywell are pretty proud of the adaptive control work that we've performed in the past, particularly under NASA sponsorship. This chart shows some of the more recent efforts at the Honeywell Systems and Research Center. This figure shows some successful adaptive work that we've done with NASA and also a very effective technology spinoff. Without going into detail, we essentially used the techniques we developed for the F-8 aircraft and the CH47 helicopter (which were demonstrated at Dryden in 1977) to design an off-shore drilling ship positioning concept that is now in production.

ADAPTIVE CONTRACTS WITH HONEYWELL

F-8C DESIGN (1974 - LRC)
FLIGHT TEST (1977 - DFRC)



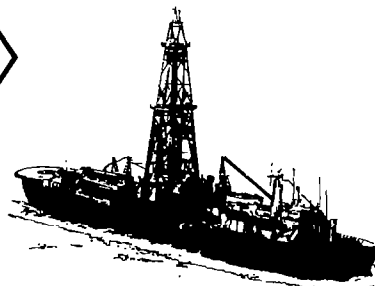
VALT DESIGN (1977 - LRC)



EXXON/HONEYWELL DEVELOPMENT (1979)

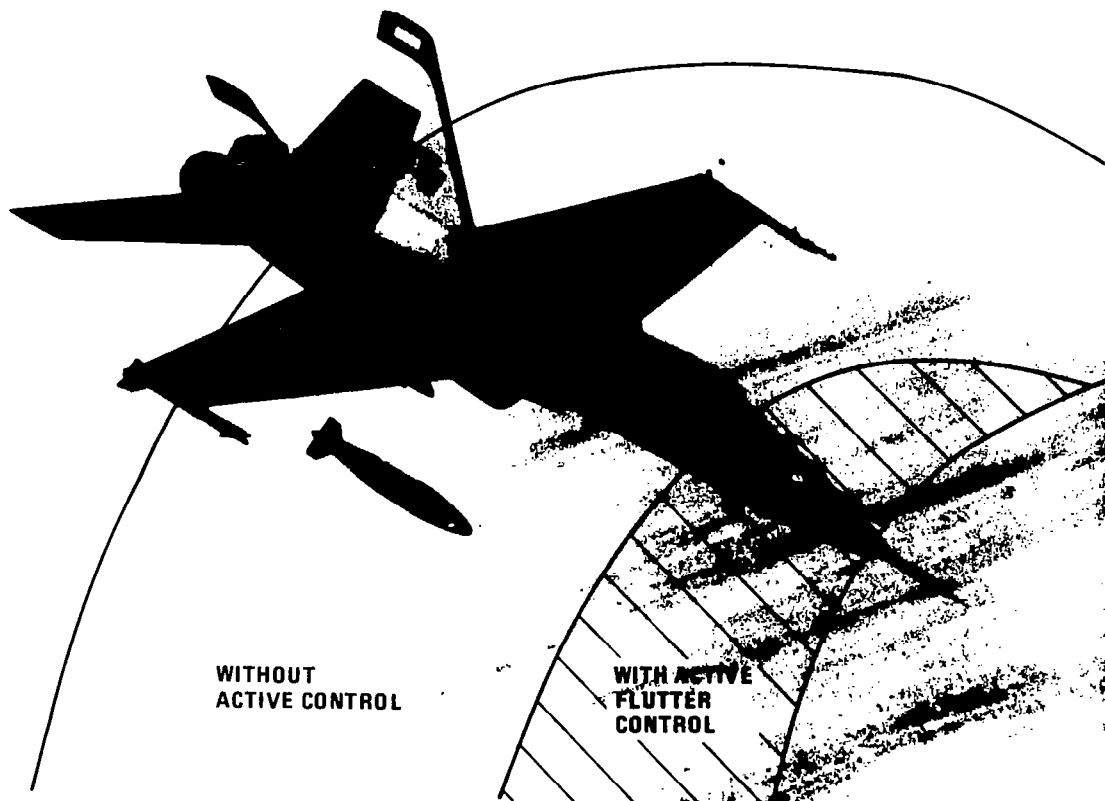
DEEP WATER OFFSHORE
DRILLING SHIP
ADAPTIVE CONTROL

TECHNOLOGY
SPINOFF



ACTIVE FLUTTER CONTROL

Active flutter control has some obvious payoffs that have been recognized for a number of years. The technology necessary to perform this is not mature and also the notion of active flutter mode control, particularly the frequencies we're dealing with, is a risky business. It is one problem to stabilize an airfoil flutter condition on a wing with known characteristics, however, from a practical standpoint, future fighter aircraft flutter mode control needs to deal with wings that have numerous dynamic configurations due to the different kinds and placements of stores.



ADAPTIVE CONTROL

This leads us to a body of work that exists in adaptive control which has some demonstrated potential in dealing with this. The issue is to identify very rapidly the onset of a dynamic change in a configuration and to modify the control structure accordingly. A concept, based upon maximum likelihood estimation, has been demonstrated in wind tunnel tests of active flutter control with wing store changes.

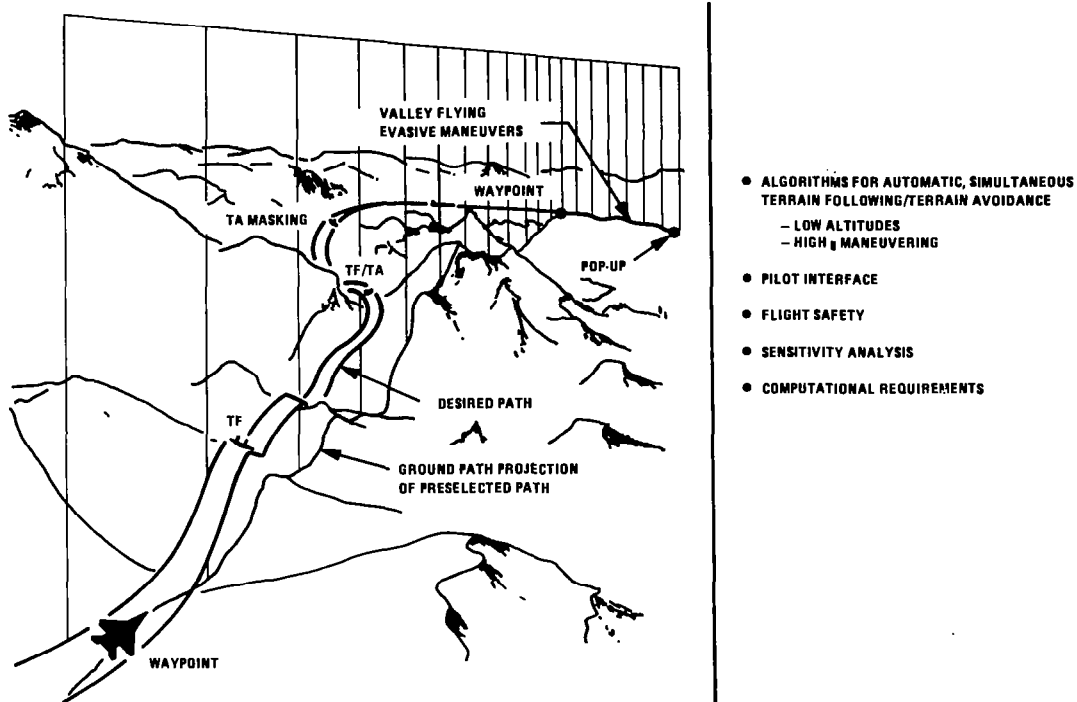
Another payoff area for adaptive control deals with the prospect of doing onboard real-time reconfigurations due to battle damages for future military aircraft.

RAPID PARAMETER IDENTIFICATION:

- **ACTIVE FLUTTER CONTROL WITH CHANGING CONDITIONS**
- **BATTLE DAMAGE RECONFIGURATION**

ADVANCED AUTOMATIC TERRAIN FOLLOWING/TERRAIN AVOIDANCE

The final two areas are combined treatment of low-level penetration and improved "ilities." This figure points out one area of great interest within DoD; this is the notion of combined terrain following/terrain avoidance and threat avoidance. As shown schematically, this involves flying very low altitudes automatically while incorporating high g maneuvers, appropriate pilot interface, and a high level of flight safety. All of the avionics subsystems which interface to attack this problem become flight safety crucial. This would certainly include the guidance portion of the flight control area, navigation, and portions of the mission management.



LOW-LEVEL PENETRATION

In addition to the fixed-wing terrain following/terrain avoidance and threat avoidance, there is an emerging set of concepts that the Army would like to develop for a single-seat light helicopter for nap-of-the-Earth flight. The challenge that I believe exists is to somehow integrate flight, navigation, propulsion, weapons, etc., in a fault-tolerant system to allow us to do nap-of-the-Earth flight with high performance and a high degree of safety.

One research area is sensor blending. I think our estimation technology applies here. We also need more creative failure management solutions. Again, I think estimation technology applies, such as expanding upon things like analytic redundancy, plus development of emerging AI concepts based on expert systems and advanced planning. Also there is this critical need to automate verification and validation of systems, both the hardware and the software, for future flight management systems. And finally in the area of flight path management, we need to somehow go down the road and actually install trajectory optimization capabilities that operate in real time for onboard applications. In addition to that, there are some front-end decision making functions that perhaps could be handled by AI planning concepts.

EXAMPLES

- AUTOMATIC TF/TA/DA
- SINGLE-SEAT LIGHT HELICOPTER - NOE

CHALLENGE

- FAULT-TOLERANT INTEGRATED FLIGHT/NAV/
PROPULSION/WEAPONS

RESEARCH AREAS

- SENSOR BLENDING - ESTIMATION
- CREATIVE FAILURE MANAGEMENT
- ESTIMATION, AI
- AUTOMATED VERIFICATION AND VALIDATION
- FLIGHT PATH MANAGEMENT - TRAJECTORY
OPTIMIZATION, AI