MEMORANDUM LR-653

The Advanced Automatic Flight Control Systems project

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SUMMARY

This memorandum provides the reader with a detailed overview of the Advanced Automatic Flight Control Systems (AAFCS) research project, pursued by the Disciplinary Group for Stability and Control, Faculty of Aerospace Engineering, Delft University of Technology (TUD).

Since the start of the project in 1978, an ever growing number of students have devoted their research efforts to the realization of a thorough foundation of knowledge and a number of practical applications in the field of automatic flight control. Hardware, ranging from a moving-base flight simulator to a fully equipped DHC-2 'Beaver' laboratory aircraft, has enabled the students to apply the results of their theoretical research to the practice of real flight.

The main text of this memorandum is devoted to the current subprojects which make out the AAFCS research project, and the hardware — both in-use and projected — that can be put to use in AAFCS research at the TUD. The list of publications, presented in an Appendix to this text, constitutes a good indication of the work done so far.
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Chapter 1. Introduction

Future transport and fighter aircraft will depend on advanced flight control systems for precise control of their flight path (aircraft guidance) and attitude (aircraft control) during all phases of flight, including take-off and landing. These flight control systems will also serve to control structural flexing and to account for inherent static instabilities. These latter two functions of advanced flight control systems significantly affect the conceptual design of future aircraft.

The advent of cheaper, faster and more reliable digital processors and memory capacity accelerated the development of capable high-authority automatic flight control systems which at present already lead to better fuel economics, more efficient flight profiles, lower maintenance costs, lower structural weights, better handling qualities and a better 'turbulence ride'. This array of advantages elucidates the interest shown by many aircraft producers and operators. It also makes clear that the gathering and consolidation of knowledge in this field by research institutes in the Netherlands is seen to be of prime importance.

Precise control in all phases of flight presupposes on the one hand an adequate control infrastructure (actuators, computers, sensors) and compared to earlier lower gain flight control systems, a more refined control system design methodology as offered by new control-theoretical developments.

The development of technology for advanced automatic flight control systems as needed for precise flight control in all phases of flight is not possible if it is based only on theoretical studies and computer simulations. It is essential to evaluate and demonstrate new design procedures and control algorithms in real flight. Evaluation in real flight offers not only a very attractive challenge to scientists and engineers, it also convincingly demonstrates the expertise and ability of Delft University of Technology (TUD) and cooperating institutes and groups to third parties.
First flight tests by the end of 1989 showed unstable closed-loop responses in several different autopilot modes. These control loops were subsequently redesigned using more detailed mathematical models of the aircraft flight control system. This led to a series of successful flight tests in 1990.

The DVB project is now referred to as the Advanced Automatic Flight Control Systems (AAFCS) project: the latter is a free English translation of DVB. The AAFCS project is organized in terms of several (sub)projects, the description of which forms the next Chapter. Students would do their graduate research on a subject in one of these (sub)-projects.

A description of the hardware and software developed so far in the AAFCS project is presented in Chapter 3. Chapter 4 treats several projected hardware developments. Appendix A comprises a list of graduate theses (and other publications), published within the framework of the AAFCS project.
Chapter 2. Description of AAFCS (sub)projects

A3.51.78.3: Output feedback systems

During the second phase of project A3.51.78 — titled digital flight control techniques and forming the main part of the DVB project — the human pilot is not any longer part of the control loop. Instead the control signals calculated by the Rolm 1603 Flight Control Computer are sent to the electro-hydraulic flight control system of the laboratory aircraft. The software of the FCC contains so-called 'control laws', these are mathematical algorithms which produce calculated flight control signals, based on several dynamic and kinematic input signals provided by the aircraft's sensors.

In this subproject, the control laws are designed by making use of the optimal output feedback computation technique. Application of this design technique results in optimal gain factors for a number of previously selected feedback signals in the sense of a quadratic cost criterion comprising aircraft state variables (i.e. dynamic and kinematic quantities) and aircraft input variables (control surface deflections and engine control parameters).

A3.51.78.4: State variable feedback systems

In this project, the design technique used for the development of the FCC control laws is known as state variable feedback.

Making use of this technique, first the state vector of the system to be controlled (i.e. the aircraft and the engine) is reconstructed, based on incomplete output signals of the system and taking into account the finite measurement accuracy of the sensor system. Next, in principle all reconstructed elements of the state vector are fed back. Finally, with respect to a quadratic cost criterion containing the state vector elements and the input signals, the elements of the feedback matrix can be calculated, by which the control law has been determined.
A3.51.78.5: Adaptive feedback

The design techniques using output feedback and state feedback (see subprojects A3.51.78.3 and -4) are based on the use of linearized system equations. The consequence of this is that the developed control laws (i.e. the elements of the feedback matrices) in general are optimized for just one nominal flight condition, from which in theory only small deviations are allowed. When the aircraft flies at an altitude, airspeed or configuration different from this nominal flight condition, performance of the control laws is degraded, sometimes even leading to instability.

One way to deal with this problem is by providing a so-called adaptive feedback. This feedback makes use of a real-time identification of the aircraft's model parameters, based on accurate sensor data. Based on these model parameters, the elements of the feedback matrix are computed, thereby taking the instantaneous flight condition as the nominal 'design point'.

Adaptive control offers good perspectives for flight control system use, since the enormous computing power required for real-time model identification and control law computation has become available at reasonable cost. Moreover, the accuracy of the aircraft's sensors, to which the control system is quite sensitive, has improved significantly.

A3.51.83.1: Multivariable design techniques in the frequency domain

The design techniques used in this subproject are based on the consideration of aircraft flight control as being a multivariable control problem. By doing this, the inherent interactions and cross-couplings of the aircraft and engine control systems are taken into the control law design, which improves control law performance. A number of multivariable control system design techniques that have been developed recently work in the frequency domain.
A3.51.84.1: Iron bird evaluation of the autopilot control laws

Before the control laws, developed for the autopilot in the project A3.71.78 — digital flight control techniques — can be implemented in the Rolm 1603 digital FCC, they have to be tested in their complete and integrated format during a simulation with a non-linear aircraft model. The flight simulator is attached to the software program so that test pilots can evaluate control law performance as well as possible.

During this so-called iron bird test, the control laws operate in an environment which closely approaches reality by incorporating nonlinearities, stochastic disturbances (turbulence) and cross-coupling effects. Also the transitions between subsequent autopilot modes are checked. The electro-hydraulic control systems for the elevator, ailerons and the rudder are simulated by linear mathematical models, based on flight test data.

The iron bird tests have a mainly qualitative character.

A3.51.78.2: Software implementation in the digital flight control computer

During the second phase of project A3.51.78 — digital flight control techniques — control laws are developed for the autopilot in the DHC-2 'Beaver' laboratory aircraft. These control laws have to be implemented in the Rolm 1603 flight control computer and thoroughly tested for their good operation before any evaluation in real flight can start (see also the previous subproject). The software implementation encompasses reprogramming the control laws in assembly language and static and dynamic testing of the Rolm's software before and after installation in the aircraft.

A3.51.85.1: Robust feedback systems

Normally, the design of aircraft flight control systems is based on the aircraft's linearized equations of motion. The parameter values in these equations (the stability derivatives and inertia parameters) are valid for only one nominal flight condition.

To ensure acceptable controller performance in a large part of the aircraft's flight envelope, the control laws either have to adapt to the changing flight condition (see subproject A3.51.78.5 — adaptive feedback), or they have to be more or less insensitive to
these changes. Control systems fulfilling the latter requirement are called \textit{robust control systems}. They may in principle be quite simple of structure.

Within the framework of this subproject, robust control systems will be developed and evaluated in real flight.
Chapter 3. Current state of affairs in the Advanced Automatic Flight Control Systems project

Section 3.1. Hardware inventory

3.1.1. The 'Beaver' experimental aircraft

One of the most imagination-striking assets in the Faculty's research tool inventory is the De Havilland Canada DHC-2 'Beaver' experimental aircraft, registered PH-VTH. This all-metal high-winged seven-seater is powered by a 450 bhp radial piston engine driving a two-bladed constant-speed propeller, see also figure 1 and the table below.

<table>
<thead>
<tr>
<th>Specifications of the 'Beaver' experimental aircraft PH-VTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft type: DHC-2 'Beaver'</td>
</tr>
<tr>
<td>Manufacturer: The De Havilland Aircraft of Canada Ltd.</td>
</tr>
<tr>
<td>Registration: PH-VTH</td>
</tr>
<tr>
<td>Serial number: 1244</td>
</tr>
<tr>
<td>Year of delivery: 1958</td>
</tr>
<tr>
<td>Wing span: 14.62 m</td>
</tr>
<tr>
<td>Overall length: 9.25 m</td>
</tr>
<tr>
<td>Empty weight: 14 900 N</td>
</tr>
<tr>
<td>Maximum take-off weight: 22 700 N</td>
</tr>
<tr>
<td>Wing area: 23.23 m²</td>
</tr>
<tr>
<td>Mean aerodynamic chord: 1.5875 m</td>
</tr>
<tr>
<td>Wing sweep: 0 deg</td>
</tr>
<tr>
<td>Wing dihedral: 1 deg</td>
</tr>
<tr>
<td>Engine type: Pratt &amp; Whitney Wasp Jr. R-985-B5</td>
</tr>
<tr>
<td>Number of cylinders: 9, radially mounted in a single row</td>
</tr>
<tr>
<td>Maximum power: 470 bhp (350 kW)</td>
</tr>
<tr>
<td>Propeller: Two-bladed all-metal variable pitch</td>
</tr>
</tbody>
</table>
The 'Beaver' is an STOL (Short Take-Off and Landing) aircraft, which implicates that it is capable of flying at very low indicated airspeeds. This is made possible by powerful wing flaps, combined with so-called 'flaperons': the ailerons 'droop' in unison with the flaps, thereby producing even more lift. Together with the asymmetric thrust effects of the powerful engine, this accounts for a very nonlinear behavior of the aircraft, especially at low airspeeds. Modelling the aerodynamics was therefore a special challenge, which has been met with acceptable accuracy only relatively recently.

![Figure 1. The De Havilland DHC-2 'Beaver' laboratory aircraft](image)

Since the Faculty acquired the aircraft from the factory in 1958, the 'Beaver' has flown some 3000 hours during which a large number of flight tests and measurements were carried out. In addition to this, many students were shown the 'real world' of stability and control theory during practical course flights. The aircraft is operated by the Disciplinary Group for Stability and Control of the Faculty of Aerospace Engineering. During the last few years, the test flights were mainly devoted to the development and evaluation of dynamic flight test manoeuvres, aerodynamic and engine model identification and automatic flight control system research. An important spin-off of the latter subject has been the acquisition of flight test data for the identification of a mathematical model of the Hydraulic Control System (see below).
3.1.2. The Hydraulic Control System

The Hydraulic Control System (HCS) is part of the Beaver’s control actuation system, see figure 2. It converts the electronic command signals coming from the Flight Control Computer (FCC) into the physical control power, needed for deflecting the aircraft’s control surfaces against aerodynamic and inertial loads. For this purpose, it contains three electro-hydraulic linear servo motors (one for each control surface), as depicted in figure 3.

![Diagram of the Beaver's Hydraulic Control System](image)

*Figure 2. Principal components of the Beaver’s Hydraulic Control system*

The servos were produced within TUD and have hydro-static piston bearings for extreme accuracy and linearity. They are controlled by Moog electro-mechanical control valves, known for their high bandwidths.

The required hydraulic pressure of 3000 psi is delivered by an engine-driven hydraulic pump, or by an auxiliary ground pump when the engine is not operating. The electronic input signals are processed by special analog servo drivers, also developed by TUD.

The control power generated by the servos is transferred to the control surfaces by the
Figure 3. TUD's electro-hydraulic servo with hydro-static bearings

aircraft's own flight control cable linkages. While this configuration provides maximum safety (the control cables are not physically interrupted), the added inertia of the control column and rudder pedals imposes rather severe bandwidth limitations on the system.

Since the 'Beaver' is used as a research tool, flight safety standards have always been closely scrutinized by both the Faculty's flight department and the Dutch Civil Aviation Authority RLD. Safety is important especially in AAFCS research, where the experimental autopilot takes over control of the aircraft. So, a number of HCS safety features, supplementary to the standard safety measures, have been added:

<table>
<thead>
<tr>
<th>HCS safety features</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electro-mechanical clutches.</strong> These provide the actual controllable connection between the servos and the linkages. The clutches establish a mechanical coupling upon receiving an electronic control signal. Following another signal, the connection can be terminated. This termination occurs upon every sensed system failure, thus providing redundancy in combination with the safety devices listed below;</td>
</tr>
<tr>
<td><strong>Shear pins between the servos and the cable system.</strong> These break at a specified force limit. The pilot can at all times disconnect the AFCS from the control linkages by manually breaking one or more shear pins (this is done by rigorously moving the controls);</td>
</tr>
<tr>
<td><strong>Pressure limits switches.</strong> These disconnect the pressurized oil flow from the system in case the pressure limits are trespassed;</td>
</tr>
<tr>
<td><strong>A quantity limit switch.</strong> These switches disengage the electro-mechanical clutches in case of an oil leak;</td>
</tr>
<tr>
<td><strong>A shear pin between the hydraulic pump and the engine.</strong> This pin breaks when the rpms of the engine and the engine-driven hydraulic pump differ too much, thus protecting the expensive engine and pump from physical damage;</td>
</tr>
<tr>
<td><strong>Servo limit switches.</strong> These assure that the servo piston ranges are smaller than the control surface ranges, this inhibits the servos from pulling the linkages against the hard stops near the control surfaces;</td>
</tr>
<tr>
<td><strong>Pressure differential limiters.</strong> These devices limit the pressure differential across the servo piston heads (this is proportional to the piston force).</td>
</tr>
</tbody>
</table>
The pilot can control the HCS through a cockpit-mounted panel. The main system power, the electro-mechanical engage clutches and the safety shear pins are controlled and monitored from this panel. Hydraulic power is fed to the servos by a selector valve which controls the direction of the pressurized oil flow coming from the engine-driven pump: through the servos or directly back into the return line. In this way, the load can quickly be removed from the system. The disengage or 'manual cut-out' switches for manual disengagement of the system are located on the control wheel and on the side stick for easy pilot access. These switches control the electro-mechanical clutches.

3.1.3. The Electric Throttle Actuation System

For the execution of a fully automated flight, apart from the aerodynamic control surfaces, the engine controls must be controlled by some regulator (called autothrottle) as well. The electronic output signals of the regulator are transformed into physical engine control inputs by the Beaver’s Electric Throttle Actuation System, see figure 4.

![Figure 4. The Beaver’s Electric Throttle Actuation System](image)

Of the three main engine control parameters, namely manifold inlet pressure, engine rpm and fuel mixture, only the first two are actuated by standard clutch-equipped King electric
servos. The mixture control is dependent on altitude and needs to be set by the pilot only once — to the 'auto' position.

3.1.4. The Flight Control Computer and associated systems

The Flight Control Computer (FCC) can be considered the heart of the AFCS in that it contains and executes the software-coded autopilot or fly-by-wire control laws. Apart from being able to resist the environmental challenges associated with flight, the FCC must also be capable of inputting signals from various sources (i.e. having different characteristics) and sending (analog) command signals to the control surface actuation system, and status signals to the annunciator panel in the cockpit.

Figure 5. The Rolm 1603 Flight Control Computer
The FCC currently in use with the Disciplinary Group is a Rolm 1603 16-bit general-purpose processor. This computer is designed and built especially for operation in severe environmental conditions (Its primary application is in military air- and shipborne electronic systems). Its specifications are given in the table below:

<table>
<thead>
<tr>
<th>Specifications of the Rolm 1603 AN UYK-27 general-purpose processor</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 bits Central Processing Unit with Extended Arithmetic Unit</td>
</tr>
<tr>
<td>Memory for 18K data words of 16 bits each</td>
</tr>
<tr>
<td>Clock frequency:</td>
</tr>
<tr>
<td>Temperature operating range: -25°C to +75°C</td>
</tr>
<tr>
<td>Weight: 25 kg with 16K memory</td>
</tr>
<tr>
<td>Connectors: MIL-C-81511 (standard)</td>
</tr>
<tr>
<td>Dimensions: 19.35 x 25.70 x 49.86 cm</td>
</tr>
<tr>
<td>Power supply: 115 VAC, 47-400 Hz, 150 W max</td>
</tr>
<tr>
<td>Combination input/output interface with additional real-time clock</td>
</tr>
<tr>
<td>16 bit parallel input/output buffer</td>
</tr>
<tr>
<td>Analog to digital converter with 16-channel multiplexer</td>
</tr>
<tr>
<td>Digital to analog converter with three independent channels</td>
</tr>
<tr>
<td>Synchro to digital converter with 8-channel multiplexer</td>
</tr>
</tbody>
</table>

The internal structure of the Rolm FCC is depicted in figure 6. It shows the presence of an Extended Arithmetic Unit (EAU) for faster processing of floating point operations.

Several interfaces, providing communication capability with external devices are connected to an internal I/O bus:

<table>
<thead>
<tr>
<th>Rolm's external interfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>For incoming signals from analog external devices, the Rolm has an Analog to Digital Converter (ADC) with a 16-channel multiplexer. For the outputs, which have to be converted into analog signals, the Rolm uses 3 separate Digital to Analog Converters (DACs). The latter are used for the output of command signals to the Hydraulic Control System (HCS).</td>
</tr>
<tr>
<td>For incoming synchro signals, a Synchro to Digital Converter (SDC) and an 8-channel multiplexer are installed.</td>
</tr>
<tr>
<td>Incoming and outgoing discrete signals (switch positions, valid flags, annunciator lights etc.) are handled by a 16 bit parallel I/O buffer (PI/OB).</td>
</tr>
</tbody>
</table>
A real time clock is incorporated as well. It is used as a control cycle timer. This brings us to the main operational deficiency of this particular type of FCC: it is not fast enough for advanced real-time control solutions. At present, the Rolm is programmed for a conventional three-axis autopilot function, which takes slightly less than 100 msec of processing time (see Chapter 3). The cycle interrupt is therefore set at exactly 100 msec. Together with the inherent computational delay of one cycle, this rather long cycle time induces sometimes barely acceptable phase lags.

The Rolm's place in the Automatic Flight Control System environment is depicted in figure 7.

To reduce the loss of computation speed as much as possible, the software is programmed in assembler on a standard PC and, upon completion, cross-compiled into octal code. This octal code is then loaded into the Rolm. Progress monitoring of the program and tracking down programming errors can be done with a special on-line debugger. Assembler code allows for reasonable high computational speeds, but it is very sensitive to programming errors. One faulty source code line can crash the entire program, even to the extent that the whole operating system has to be reloaded.

A new, more powerful multiprocessor system (as described in Chapter 4) is presently being acquired to overcome these problems.
3.1.5. The A3A Data Logging System

For the execution of relatively simple in-flight and on-ground measurements, a measurement and registration system has been developed. This system was dubbed A3A Data Logging System, abbreviated to DLS. The topology of the system is depicted in figure 8.

The system records electronic signals coming from several aircraft sensors on either an audio tape or a hard disk unit. Before recording, the system converts the incoming signals to a digital format with radix\(^\text{1}\). These digital representations of the measured signals can then be recovered and processed on the ground. The recovery mainly consists of time-shifting and calibrating operations on the signals, resulting in synchronous data in engineering units. A number of specialized software programs have been written for this purpose, to be used on the Disciplinary Group’s Encore supermini computer.

The system can perform 2000 sequential measurements per second at maximum, dispersed over 16 channels maximum. Every signal can thus be recorded at least 125 times per second.

To the data signals, a time signal and a number of control and identification bits are

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\(^{1}\) A radix is the base number on which a numeric system is based; our common decimal numeric system has radix 10. A system with radix 8 is therefore an octal system.
added. These aid the data recovery software in regaining the original sensor signals. The main processing software packages (identification, determination of inertia properties, plot programs) are also implemented on the Encore supermini computer. The recovered data from the DLS can therefore be taken into these programs directly.

Over the years, operators of the DLS have gained a thorough insight in the specific problems regarding the transform of analog data into sequential, non-synchronized digital bits and the recovery of as much original data as possible, especially when the sampling frequency is low compared to the highest system eigenfrequency.
Section 3.2. Additional facilities

3.2.1. The moving-base flight simulator

Since 1971, the Disciplinary Group owns and operates a moving-base flight simulator with three degrees of freedom: three hydraulic jacks can simulate heave (=vertical translation), pitch and roll motions. Each jack is driven by a separate analog signal to limit values of 30 centimetres above and below the datum position. The pistons within the jacks are provided with hydrostatic bearings for very low friction and noise levels. A cutaway view of the simulator is presented in figure 9.

![Diagram of the moving-base flight simulator](image)

Figure 9. The Faculty's moving-base flight simulator.

One very important input to the flying pilot is the control force that he feels through his flight controls (i.e. control yoke, wheel and rudder pedals). A special analog computer provides the feedback of aerodynamic and inertial loads on the control surfaces to the flight controls. This control loading is generated by small hydraulic actuators.

The outside world is simulated by a digital night vision system. This generates a dimly lit horizon bar and the lighting systems of Amsterdam Airport's runway 06 and its surroundings. These images are displayed on beam penetration CRT screens and projected through
the cockpit windows via a collimating mirror. In this way, the pilot has to adjust his eyes to infinite distance in order to focus on the generated display, in spite of it being generated only a few feet from his eyes.

Aural impressions to the pilot are provided by the aural simulation system, consisting of variable frequency oscillators. The distinct sound of turbofan engines is sent through loudspeakers behind the seats of the pilots. The pitch of the sound is depending on simulated engine rpm, while the intensity is made a function of airspeed.

Since the simulator is used only for research and educational purposes and not for flight crew training, the environmental cue fidelity\textsuperscript{2} is high and the equipment cue fidelity need only be medium. (The operators need not train themselves in cockpit procedures.) The equipment cues are provided by the following cockpit instruments:

\begin{table}[h]
\centering
\begin{tabular}{|l|}
\hline
TOD simulator cockpit instruments \\
\hline
attitude director indicator with flight director bars \\
horizontal situation indicator with DME readings \\
airspeed indicator \\
barometric and radio altimeters \\
vertical speed indicator \\
engine instruments fitted for two turbofan engines \\
flap and trim position indicators \\
two separate AFCS control panels and an annunciator panel \\
\hline
\end{tabular}
\end{table}

Over the years, several students and teams of students have in the frameworks of their graduate research developed and implemented various aircraft models. Within minutes, one can select one of the following aircraft and fly it in its full flight regime,

\textsuperscript{2} This is the quality of the inputs to the pilot's sensory system, generated by the motion, visual and aural simulation systems.
**TUD simulator: implemented aircraft models**

<table>
<thead>
<tr>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>De Havilland DHC-2 'Beaver'</td>
</tr>
<tr>
<td>Boeing B747</td>
</tr>
<tr>
<td>Cessna Citation 500</td>
</tr>
<tr>
<td>Casa/IPTN CN235</td>
</tr>
<tr>
<td>Piper Seneca</td>
</tr>
<tr>
<td>Aerospatiale AS365 'Puma' (a helicopter)</td>
</tr>
</tbody>
</table>

The implementation of new aircraft models was made far easier by the adaptation of a highly modular software structure some years ago. Since then, detailed turbulence, windshear and AFCS models have been added as individual subroutines for additional quality-improving simulation features.

3.2.2. The Encore 32/87 supermini computer

The Disciplinary Group owns and operates an Encore 32/87 supermini computer for the simulation of aerospace vehicles and systems and other real-time applications, and for the development of new software related to the Group's research. Its specifications are listed below,
### Encore 32/87 specifications

<table>
<thead>
<tr>
<th>Type:</th>
<th>32 bit supermini</th>
</tr>
</thead>
</table>
| Memory: | 4 Mb RAM  
32 kb cache |
| Secondary memory: | 1 80 Mb disk unit with interchangeable disk-pack  
1 340 Mb Winchester drive  
2 1.6 Mb 8” floppy disk drives  
1 tape unit: 800/1600 bpi, 45 ips |
| User interfaces: | 7 terminals  
1 line printer  
2 plotters  
1 laser printer  
3 IBM PCs (via Kermit) |
| Operating system: | MPX-32 real-time O.S. |
| I/O controllers: | Z-card (for interface with flight and satellite simulators);  
Universal I/O Controller (UIOC; for motion system identification, side stick control and display control in man-machine interface applications) |

#### 3.2.3. The 'Fortran Autopilot' off-line simulation software package

Any automatic flight control (sub)system design should be thoroughly evaluated before it is experimented with in real flight. The reason for this is obvious: since any design is based on a mere approximation of reality, it may perform less well than predicted when subjected to real flight. Also, design and implementation errors have to be eliminated before the AFCS takes over control of the aircraft. The Disciplinary Group has developed a number of test methods for every aspect of the process from control law design to implementation. One of these methods consists of off-line simulation of the complete aircraft-plus-autopilot system on the Encore supermini computer. The simulation package features a non-linear aircraft model connected to a complete version of the autopilot software. In this way, important performance influencers such as model nonlinearity, mode controller and engage fader interference, engine and flap-induced forces and moments and turbulence can be taken into account. Although the program package is not yet entirely finished, most of the test capabilities are at present available. As with all research tools, special attention is given to clarity and understandability of the simulation package’s source code. Therefore, the package consists of a set of subroutines with clearly defined
functions and tasks.
Further refinements to the program comprise the inclusion of on-line simulation and a better HCS model, and more attention to user-friendliness.

Section 3.3. The automatic flight control software package

3.3.1. Introduction

The function of an autopilot is to control the aircraft so that it will follow a predetermined flight path. Several of these flight paths are defined and can be selected by the pilot through a cockpit-mounted panel. The autopilot's architecture is shaped around different sorts of flight paths: every flight path has its own characteristics (e.g. constant altitude, tracking a VOR radial). The software that guides the aircraft along a certain path is called an autopilot mode.

Like many autopilots up to this date, the Beaver's Digital Autopilot (BDAP) is designed with linear systems theory and a separation of aircraft motions into longitudinal/vertical and lateral-directional movements. In fact, it is based on an existing analog autopilot, the King KFC-300. Both autopilots control the lateral-directional aircraft motions with the ailerons and rudder, and the longitudinal/vertical motions with the elevator. Cross-coupling are taken into account only to a very limited extent. The predetermined flight paths and hence the autopilot modes are because of this separated into the same categories, with the additional separation of the lateral-directional modes into lateral and directional:
<table>
<thead>
<tr>
<th>BDAP longitudinal/vertical modes</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch Attitude Hold (PAH)</td>
<td>Keeps the aircraft steady at the pitch angle</td>
</tr>
<tr>
<td>Altitude Hold (ALH)</td>
<td>Controls the aircraft so that it will hold the altitude constant at the value that existed at the time of engagement of this mode.</td>
</tr>
<tr>
<td>Altitude Select (ALS)</td>
<td>Commands the aircraft to a predetermined altitude with constant vertical speed (which is not the right concept: it should control the aircraft to maintain an airspeed for optimum climb performance) and then switches over to the ALH mode to maintain that altitude.</td>
</tr>
<tr>
<td>Approach/Glide Slope (APP/GS)</td>
<td>Commands the aircraft along the glide slope datum line, created by signals from the ILS glide slope transmitter. Always used in combination with Approach/Localizer (see below).</td>
</tr>
<tr>
<td>Go Around (GA)</td>
<td>This mode commands the aircraft to the go around pitch angle $\theta_{GA} = +10^\circ$. Always used in combination with the lateral part of the GA mode (see below).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BDAP lateral modes</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll Attitude Hold (RAH)</td>
<td>Keeps the aircraft at the bank angle that existed at the time of engagement of this mode.</td>
</tr>
<tr>
<td>Heading Hold/Select (HH/HS)</td>
<td>Steers the aircraft onto the heading that existed at the moment of engagement of this mode (Heading Hold), or onto a heading selected by the pilot through a pointer on the compass scale of his Horizontal Situation Indicator (Heading Select).</td>
</tr>
<tr>
<td>Navigation (NAV)</td>
<td>Commands the aircraft to track a VOR radial, selected by the pilot.</td>
</tr>
<tr>
<td>Approach/Localizer (APP/LOC)</td>
<td>Commands the aircraft along the runway extended centerline, defined by the signal from the ILS localizer transmitter.</td>
</tr>
<tr>
<td>Go Around (GA)</td>
<td>This mode commands the aircraft to the go around bank angle $\theta_{GA} = 0^\circ$.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BDAP directional 'autopilot mode'</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw Damper (YD)</td>
<td>Dampens the dutch roll and adverse yawing while rolling into a turn. Keeps the side slip angle as small as possible.</td>
</tr>
</tbody>
</table>

The PAH, RAH and YD modes are so-called 'inner loop modes': these actually control the aircraft towards specified reference flight conditions. The other loops are called 'outer loop modes': these provide the inner loops with guidance signals, related to the desired flight path. As can be deduced from the above, the autopilot uses different control laws for different desired flight paths. Most of the modes have in fact more than one control law at their disposal; in this case we speak of submodes. The autopilot contains a special
subprogram that selects which control law should be used, based on input information both from the pilot and from the aircraft’s sensors. This subprogram is called the mode controller. Together with the library of control laws, the mode controller forms the actual autopilot software, as opposed to the signal conditioning and utility routines. Figure 10 further illuminates this architecture.

![Diagram of input and output routines](image)

Figure 10. Beaver’s Digital Autopilot structure.

### 3.3.2. The BDAP software

The Beaver's Digital Autopilot (BDAP) is a research tool. This means that corrections to and amendments of its software must be easy to implement. Hence the software implemented in the Rolm FCC has a highly modular structure, which makes it easy to trace and to include new program elements, e.g. control laws. The readability of the source code is made a bit difficult by the computer language that was used: assembly. The cross-compiler provides ample space for comments, however. The principal modules are shown in the figure below. They will be discussed shortly.
## Principal BDAP software modules

<table>
<thead>
<tr>
<th>Module</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master module</td>
<td>Controls the execution of the program by starting the modules at specified time points within the 100-millisecond cycle.</td>
</tr>
<tr>
<td>Data Input module</td>
<td>Reads analog and digital input data. Generates digital data words important to the mode controller: they contain status information on engaged modes, signal valids etc.</td>
</tr>
<tr>
<td>Mode Controller module</td>
<td>Contains logic which checks whether any mode or submode change should be commanded. A so-called engage fader takes care of smoothing transitions from one (sub)mode to another by mixing new and old signals for a few seconds.</td>
</tr>
<tr>
<td>Flight Control Routine library</td>
<td>Contains the control laws from which the mode controller chooses the one to be processed.</td>
</tr>
<tr>
<td>Data Output module</td>
<td>Takes care of the output of control surface deflection command signals and annunciator light signals.</td>
</tr>
</tbody>
</table>

![Diagram](image)

Figure 11. Principal BDAP software modules.
Chapter 4. Future hardware developments

Section 4.1. Wing flap actuation for the 'Beaver'

For some high-frequent longitudinal control problems (e.g. turbulence response alleviation), some form of direct lift control is needed. In these cases, the inherent non-minimum-phase nature of the elevator leaves it as insufficient for the application of control commands to the aircraft. Lift control through actuation of the wing flaps\(^3\) is far more direct: control utilizing this form of actuation are thence called 'direct lift controls'). Investigations into the aerodynamic and structural consequences of high-frequent hydraulic wing flap actuation for the 'Beaver' will be carried out in the near future. The specific construction of the Beaver's flaps\(^4\) enables high-frequent actuation from a geometrical point of view, but the structural design might not be able to withstand the associated aerodynamic and inertial loads. The aerodynamic loads on the wing as a whole play a role as well in the evaluation of the feasibility of high-frequency flap actuation. Flap-related aerodynamic derivatives like \(C_{Z_{\delta_f}}\) and \(C_{m_{\delta_f}}\) are to be identified from existing flight test data bases.

\(^3\) Using symmetrical actuation of the ailerons also works in many cases.

\(^4\) It comprises vertically offset hinges which cause the flaps to deflect in a fowler-type motion.
Figure 12. Projected wing flap actuation system.
Section 4.2. A new passive side stick

A new passive side stick is being developed in-house to overcome the disadvantages of commercially available side sticks such as the absence of (viscous) damping capabilities and the lack of decoupling between the pitch and roll stick commands. The new side stick will be designed so that none of these disadvantages will exist any more. Active side stick technology is extensively being researched in the man-machine interfacing projected, pursued within the same Disciplinary Group, but since the incorporation of artificial 'feel' in the side stick either involves much weight (electric torque motors) or high-pressure fluid near the pilots (hydraulic actuation), active side sticks are not envisioned to be installed in aircraft in the near future.

Section 4.3. The new transputer-based Flight Control Computer system

The Flight Control Computer currently in use with the Disciplinary Group does not have the capabilities needed for future applications: the now implemented classical autopilot takes up slightly less than 100 msec of computations time. Combined with the computational delay inherent to digital controllers, this cycle time induces sometimes barely acceptable phase lags. On-line identification or on-line state reconstruction routines as used in for instance adaptive control algorithms require much more computational power and would take computation times measured in seconds, instead of milliseconds. Therefore, a new Flight Control Computer system must be acquired in the near future, so that advanced theoretical concepts that are presently being developed can be tested in real flight.

Based on the development of a real-time state estimator and model identifier in the Disciplinary Group, the first configuration of the new FCC should have processing power comparable to that of four Inmos T800-20 20 MHz transputers with 2 Mb of random-

\[5\] In terms of processing speed, memory capacity and interfacing speed.
access memory each, and fast dedicated interfaces. This configuration should be able to cope with the demands of the near and mid-term future. It is of course prudent however, to bear in mind that scientists always want more, faster and more powerful computers, and that new theoretical concepts may ask for still more processing power. Thus, expandability is an important characteristic of any new FCC system.

Transputers have a big advantage here, for one can attach in principle infinitely many transputers to an existing system, without creating a bottleneck in e.g. the communications bus (each transputer brings along four high-speed serial I/O links for communication with other transputers, so that by adding more transputers the communication bandwidth will increase instead of decrease).

Source code for the current Rolm FCC is programmed in assembly code on a host computer (a PC), then compiled into octal code for computation speed. The new FCC system host computer(s) must, however, be fitted with a widely used high-level programming language, to allow more easy and flexible programming and exploitation of existing software libraries. The Ada language used and prescribed by the USA government offers many advantages, such as tasking, strong typing and separate compilation capabilities. Moreover, NLR, with which the Disciplinary Group is to start a cooperation programme on AAFCS research, have already adapted Ada as their standard AFCS programming language. A disadvantage for such an adaptation by the Disciplinary Group is that several design and evaluation tools have already been written in Fortran 77 for the Encore supermini. Thus, the introduction of Ada forces students to become familiar with two high-level programming languages.

I/O devices may be controlled by several I/O circuit boards connected to a fast communication link, such as a VME bus. This configuration, in combination with fast interfaces employing Direct Memory Access to Dual-Ported RAM and Vector Interrupting, accounts for speed, modularity and expandability. (Future congestion of the VME bus is not to be feared, since I/O capacity can be fairly accurately predicted.)

A configuration of multiple processors with fast communication buses for I/O handling also opens the possibility to gain insight in the intricacies of parallel processing, a concept which is thought to become very important in AFCS technology in the future.
Interfacing with the pilot may be carried out through a touchscreen. This eliminates the need for separate annunciator and mode controller panels, and virtually all status and warning lights. The touchscreen can also be used for the display of graphical information on e.g. hydraulic fluid pressure and temperature, and for displaying command signals. The high-speed characteristics of the FCC make it very usable for data acquisition during flight tests for post-flight AFCS performance analysis. Sampled measurements can be allotted to secondary memory, such as a g-resistant hard disk drive.

All remarks made above are put together in figure 13, displaying the proposed topology for the new Advanced Automatic Flight Control System.

Section 4.4. New aircraft sensors

During the design of new control laws or the evaluation of new control-theoretical concepts, the designer assumes that a number of input signals are provided to the Flight Control Computer with 'acceptable' accuracy. These control law input signals must be measured by appropriate sensors in the aircraft\(^6\). The 'Beaver' is at present equipped with a multitude of high-accuracy transducers. In the future, however, several additional transducers will be required, such as a radio altimeter, an inertial and a satellite navigation system.

High accuracy transducers are thought to be essential for two reasons. Firstly, in order to demonstrate the differences between control algorithms derived from different theoretical concepts, parasitical effects such as noise and unmodelled nonlinearities from sensors must be suppressed as much as possible. Secondly, these differences must be measured as accurately as possible.

\(^6\) A parameter which is difficult to measure with high accuracy can also be estimated from other, more accurate signals.
Appendix A. Graduate theses and other publications in the framework of the DVB project


