AIRBUS A320/A330/A340 Electrical Flight Controls A Family of Fault-Tolerant Systems

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Abstract

This paper deals with the digital electrical flight control system of the Airbus A320/A330/A340. The A320 was the first civil aircraft equipped with such a system. It was certified and entered into servive in the first quarter of 1988. The A330 and A340 have identical systems, closely related to the A320 system.

These systems are built to very stringent dependability requirements both in terms of safety (the systems must not output erroneous signals) and availability. The basic building blocks are fail-safe control and monitoring computers. The control channel performs the function allocated to the computer (control of a control surface for example). The monitoring channel ensures that the control channel operates correctly.

A high level of redundancy is built into the system. Special attention has been paid to possible external aggressions. The system is built to tolerate both hardware and software design faults. The A320 system is described together with the significant differences between the A320 and the A330/A340, and A320 in service experience.

1. Introduction

The first electrical flight control system for a civil aircraft was designed by Aerospatiale and installed on Concorde. This is an analog, full-authority system for all control surfaces and copies the stick commands onto the control surfaces. A mechanical back-up system is provided on the three axes.

The first generation of electrical flight control systems with digital technology appeared on several civil aircraft at the start of the 1980's including the Airbus A310 (see ref. 1). These systems control the slats, flaps and spoilers. These systems have very stringent safety requirements (the runaway of these control surfaces must be extremely improbable). However, loss of a function is permitted as the only consequences are a supportable increase in the crew's workload.

The Airbus A320 is the first example of a second generation of civil electrical flight control aircraft which includes the A340 (certified at the end of 1992). The distinctive feature of these aircraft is that all control surfaces are controlled electrically by high-level control laws in normal operation and that the system is designed to be available under all circumstances.

This system was built to very stringent dependability requirements both in terms of safety (the system must not output erroneous signals) and availability. The basic building blocks are the fail-safe control and monitoring computers. These computers have stringent safety requirements and are functionally composed of a control channel and a monitoring channel. The control channel ensures the function allocated to the computer (for example, control of a control surface). The monitoring channel ensures that the control channel operates correctly.

A high level of redundancy is built into the system. Special attention has been paid to possible external aggressions. The system is built to tolerate both hardware and software design faults. The overall dependability of the aircraft is also reinforced by the stability augmentation, and flight envelope protections provided by the system.

The aircraft safety is demonstrated using qualitative and quantitative assessments ; this approach is consistent with the airworthiness regulation. Qualitative assessment is used to deal with design faults, interaction (maintenance, crew) faults, and external environmental hazard. For physical ("hardware") faults, both a qualitative and a quantitative assessments are done. This quantitative assessment covers the FAR/JAR 25.1309 requirement, with its link between failure condition classification (Minor to Catastrophic) and probability target.

This paper is divided into 6 parts: fligh by wire basic principles, the description of the basic building blocks of the system, that is, the control and monitoring computers, the description of the A320 system from a fault-tolerant standpoint, the system validation, the description of the main differences between the A340 and the A320, and the A320 in service experience.

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2. Fly-by-wire principle

On a conventional airplane, the pilot orders are transmitted to the actuators by an arrangement of mechanical components (see figure 1.a). In addition, computers are modifying pilot feels on the controls ("feel" computers on the figure 1a), and auto-pilot computers ("A/P" on figure 1.a) are able to control the actuators.

The A320/330/340 flight control surfaces are all electrically controlled, and hydraulically activated. The Trimmable Horizontal Stabilizer and the rudder can also be mechanically controlled.

The side-sticks are used to fly the aircraft in pitch and roll (and indirectly through turn coordination in yaw). The pilot inputs are interpreted by the flight controls computers ("F/CTL computer", figure 1.b) and move the surfaces as necessary to achieve the desired flight path. In auto-pilot mode, the flight controls computers take their orders from the auto-pilot computers ("A/P computer", figure 1.b). With this respect, the A320 flight controls is composed of seven computers, and the auto-pilot of two. The flight controls computers are of a control and monitoring type, described in § 3.

The aircraft response to surfaces movement is fedback to both auto-pilot and flight controls computers through specific sensors (Air Data and Inertial Reference Units - ADIRU, accelerometers), and displayed to the crew, through dedicated screens.

3. Control and monitoring computers

Functionally, the computers have a control channel and a monitoring channel (see figure 2). The control channel ensures the function allocated to the computer (for example, control of a control surface). The monitoring channel ensures that the control channel operates correctly. This type of computer has already been used for the autopilot computers of Concorde, and the Airbus aircraft.

These computers can be considered as being two different and independent computers placed side by side. These two (sub) computers have different functions and are placed adjacent to each other only to make aircraft maintenance easier.Both command and monitoring channels of one computer are active simultaneously, or waiting, again simultaneously ,to go from stand-by to active state.

Two types of computers are used in the A320 flight control system: the ELAC's (ELevator and Aileron Computers) and the SEC's (Spoiler and Elevator Computers). These computers were designed and manufactured by different equipment manufacturers to make them tolerant to a design or manufacturing fault. Thus, the A320 has two types of computers (ELAC, SEC), each computer has a control channel and a monitoring one. Thus, four different entities coexist: control channel of ELAC computer, monitoring channel of ELAC computer, control channel of SEC computer, and monitoring channel of SEC computer. This leads to four different software packages.

Two types of computers are also used on the A340: the PRIM's (primary computers) and the SEC's (secondary computers). Although these four computers are different, the basic safety principles are similar and described in this part of the paper.

In addition to the ELACS and SECs of the A320, two computers are used for rudder control (FAC). They are not redundant to the ELACs and SECs. On A330/A340, these rudder control functions are integrated in the PRIMs and SECs.

3.1 Computer specification

The specification of a computer includes, on the one hand, an "equipment and software development" technical specification used to design the hardware and, in part, the software, and, on the other hand, an "equipment functional specification" which accurately specifies the functions implemented by the software.

This functional specification is written using a computer-assisted method: SAO (Spécification Assistée par Ordinateur = Computer-Assisted Specification", see an example in figure 3). All of the computer functions are specified with this method: flight control laws, monitoring of data, actuators, slaving of control surfaces, reconfigurations, etc.. One of the benefits of this method is that each symbol used has a formal definition with strict rules governing its interconnections. The specification is under the control of a configuration management tool and its syntax is partially checked automatically. The validation of this specification is part of the system validation, see § 4.

3.2 Computer architecture

Each channel (figure 2) includes one or more processors, their associated memories, input/output circuits, a power supply unit and specific software. When the results of one of these two channels diverges significantly, the channel or channels which detected this failure cut the links between the computer and the exterior. The system is designed so that the computer outputs are then in a dependable state (signal interrupt via relays). Failure detection is mainly achieved by comparing the difference between the control and monitoring commands with a predetermined threshold (see discussion on § 3.4). This schema therefore allows the consequences of a failure of one of the computer's components to be detected and

prevents the resulting error from propagating outside of the computer. This detection method is completed by monitoring for good execution of the program via its sequencing.

Flight control computers must be especially robust. They are especially protected against overvoltages and undervoltages, electromagnetic aggressions and indirect effects of lightning (device "P" on figure 2). They are cooled by a ventilation system but will operate correctly even if ventilation is lost.

3.3 Software

The software is producted with the essential constraint that it must be verified and validated. Also, it must meet the world's most severe civil aviation standards (level 1 software to DO178A - ref. 3). The functional specification (§3.1) acts as interface between the aircraft manufacturer's world and the software designers' world. The major part of the A320 flight control software specification is a copy of the functional specification. This avoids creating errors when translating the functional specification into the software specification. For this "functional" part of the software, validation is not required as covered by the work carried out on the functional specification. The only part of the software specification to be validated concerns the interface between the hardware and the software (task sequencer, management of self-test software inputs/outputs). This part is only slightly modified during aircraft development.

To make software validation easier, the various tasks are sequenced in a predetermined order with periodic scanning of the inputs. Only the clock can generate interrupts used to control task sequencing. This sequencing is deterministic. A part of the task sequencer validation consists in methodically evaluating the margin between the maximum execution time for each task (worst case) and the time allocated to this task.

An important task is to check the conformity of the software with its specification. This is performed by means of tests and inspections (see ref. 4). The result of each step in the development process is checked against its specification. For example, a code module is tested from its specification. This test is first of all functional (black box), then structural (white box).

Adequate coverage must be obtained for the internal structure and input range. The term "adequate" does not mean that the tests are assumed as being exhaustive. For example, for the structural test of a module, the equivalence classes are defined for each input. The tests must cover the module input range taking these equivalence classes and all module branches (among other things) as a basis. These equivalence classes and a possible additional test effort have the approval of the various parties involved (aircraft manufacturer, equipment manufacturer, airworthiness authorities, designer, quality control).

The software of the control channel is different from that of the monitoring channel. Likewise, the software of the ELAC computer is different from that of the SEC computer (the same applies to the PRIM and the SEC on the A340). The aim of this is to minimize the risk of a common error which could cause control surface runaway (control/monitoring dissimilarity) or complete shutdown of all computers (ELAC/SEC dissimilarity).

The basic rule to be retained is that the software is made in the best possible way. This has been recognized by several experts in the software field both from industry and from the airworthiness authorities. Dissimilarity is an additional precaution which is not used to reduce the required software quality effort.

3.4 Failure detection and reconfiguration

Latent failure ; Certain failures may remain masked a long time after their creation. A typical case is that of a monitoring channel made passive and detected only when the monitored channel itself fails. Tests are conducted periodically so that the probability of the occurrence of an undesirable event remains sufficiently low (i.e., to fullfill FAR/JAR 25.1309 quantitative requirement). Typically, a computer runs its self-tests and tests its peripherals during the energization of the aircraft and therefore at least once a day.

Comparison threshold - robustness ; The results are compared in the two channels. The difference between the results of the control and monitoring channels are compared with a threshold (see figure 3, the difference between the result computed by the monitoring channel - PLCURR - and the output of the control channel - ANI5-1 - is compared to a threshold of 2mA). A failure is detected if the difference between the channels is above an allowable threshold. This must be confirmed before the computer is disconnected. The confirmation consists in checking that the detected failure lasts for a sufficiently long period of time (0.05sec in the "CONF" symbol of figure 3). The detection parameters (threshold, temporisation) must be sufficiently "wide" to avoid unwanted disconnections and sufficiently "tight" so that undetected failures are tolerated by the computer's environment (the aircraft). More precisely, all system tolerances (most notably sensor inaccuracy, rigging tolerances, computer asynchronism) are taken into account to prevent undue failure detection, and errors which are not detectable (within the signal and timing thresholds) are assessed with respect of their handling quality, and structural loads effect.

Redundancy ; The redundancy aspect is handled at system level (§ 4.2). This paragraph only deals with the computer constraints making system reconfiguration possible. The functions of the system are divided out between all the computers so that each one is permanently active at least on one subassembly of its functions. For any given function, one computer is active the others are in standby ("hot spares"). As soon as the active computer interrupts its operation, one of the standby computers almost instantly changes to active mode without a jerk or with a limited jerk on the control surfaces. Typically, duplex computers are designed so that they permanently transmit healthy signals and so that the signals are interrupted at the same time as the "functional" outputs (to an actuator for example) following the detection of a failure.

4. Description of A320 system

The A320 flight controls are described elsewhere (ref. 5). We shall only deal with them here from a dependability point of view.

4.1 Flight envelope protection

One of the contributions of the electrical flight controls to the safety of the aircraft is the protections which are an integral part of the flight control laws. The structure is therefore protected during normal flying (G-load factor, speed). A third protection, called high angle-of-attack, prevents the aircraft from stalling. These protections lighten the pilot's workload, in particular, during avoidance maneuvers whether for an obstacle (near-miss) or windshear. These protections enhance safety. A pilot who must avoid another aircraft can concentrate on the path to be followed without worrying about the structural limits of the aircraft or a possible stall. Windshear generally occurs at low altitudes (see ref. 6).

4.2 Failure detection and redundancy

Detection ; Now that the benefits of an electrical flight control system have been underlined, we must now make the system sufficiently dependable. The first type of failure to be taken into account is the hardware failure of the system's equipment. As the computers are control and monitoring computers (§ 3), this makes control surface runaway by a computer extremely improbable. The failure of a computer will therefore lead to it being shut down. The actuators are monitored by the computers both by the monitoring channels and the control channels. Both channels can make the actuator passive. The various sensors (on the sticks, actuators, inertial systems, etc.) comprise another runaway source. Each sensor is at least duplicated so that all information used is consolidated by comparison between at least two different sources of information.

Redundancy ; The electrical power is normally supplied by two generators each driven by a different engine. Also, an auxiliary generator, batteries and a Ram Air Turbine (RAT) are available. If the two engines shut down, the RAT is automatically extended. It then pressurizes a hydraulic system which drives a third electrical generator. The computers are connected to at least two power sources. The aircraft has three hydraulic systems (identified by a colour, Green, Blue, and Yellow on figure 4) one of which is sufficient to control the aircraft. Two systems are pressurized by each engine, the third one being pressurized either by an electric pump or by the RAT.

The computers and actuators are also redundant (see figure 4 for the system architecture). This is illustrated by the A320 pitch control (left and right elevator, plus Trimable Horizontal Stabilizer - THS). Four control and monitoring computers are used, one is sufficient to control the aircraft. In normal operation, one of the computers (ELAC2) controls the pitch, with one servocontrol pressurised by the Green hydraulic for the left elevator, one pressurised by the Yellow hydraulic on the right elevator, and by electric motor N°2 for the THS. The other computers control the other control surfaces. If ELAC2 or one of the actuators that it controls fails, ELAC1 takes over (with the servocontrols pressurized by the Blue hydraulic on elevators, and with THS motor N°1). Following same failure method, ELAC1 can hand over control to SEC2. Likewise, pitch control can be passed from one SEC to the other depending on the number of control surfaces that one of these computers can handle. These priority orders are pictured by arrows on figure 4. Note that 3 computers would be sufficient to meet the safety objectives. The additional computer is fully justified by operational constraints: it is desirable to be able to tolerate a take-off with one computer failed.

Dissimilarity ; The flight control system was subjected to a very stringent design and manufacturing process and we can reasonably estimate that its safety level is compatible with its safety objectives. An additional protection has nevertheless been provided which consists in using two different types of computers: the ELAC's produced by Thomson-CSF around 68010 microprocessors and the SEC's with hardware based on the 80186 and built in cooperation by SFENA/Aerospatiale. We therefore have two different design and manufacturing teams with different microprocessors (and associated circuits), different computer architectures and different functional specifications. At software level, the architecture of the

system leads to the use of 4 software packages when, functionally, one would suffice.

Electrical installation ; The electrical installation, in particular the many electrical connections, also comprises a common-point risk. This is avoided by extensive segregation: in normal operation, two electrical generation systems exist without a single common point. The links between computers are limited, the links used for monitoring are not routed with those used for control. The destruction of a part of the aircraft is also taken into account: the computers are placed at three different locations, certain links to the actuators run under the floor, others overhead and others in the cargo compartment.

In spite of all these precautions, a mechanical standby system has been conserved. This mechanical system is connected to the trimmable horizontal stabilizer allowing the pitch axis and the rudder to be controlled providing direct control of the yaw axis and indirect control of the roll axis. The safety objectives for the fly-by-wire part of the system have been defined without taking credit of this mechanical back-up.

4.3 Reconfiguration of flight control laws and flight envelope protections

Note that the laws are robust as designed with a sufficient stability margin. Also, if the input vector of the system is outside a predetermined range, only a simple law, using the position of the sticks and the position of the control surfaces at input, is activated (this law is similar to the type of control available on a conventional aircraft).

The laws must be reconfigured if certain sensors are lost (in particular, the ADIRU's). The crew is clearly warned about the status of the control law. If the three ADIRU's are available (normal case), the pilot has full authority within a safe flight envelope. This safe flight envelope is provided by protections included in the control laws, by addition of protection orders to the pilot orders. Flight control is in G-load factor mode.

If only one ADIRU is available, it is partially monitored by comparison with other independent information sources (in particular, an accelerometer). In this case, the safe flight envelope is provided by warnings, as on a conventional aircraft. Flight control is still in G-load factor mode. If all ADIRU's are lost, the flight envelope protections are also lost and the flight control law is in a degraded mode: direct mode. This law has gains which are a function of the aircraft configuration (the position of the slats and the flaps) and allows here again flight control similar to that of a conventional aircraft.

5. System Validation

The system validation proceeds through several different steps:

- peer review of the specifications, and their justification
- analysis, most notably the System Safety Assessment which, for a given failure condition, check that the monitoring and reconfiguration logic allow to fullfill the quantitative and qualitative objectives, but also analysis of system performances, and integration with the structure
- tests with a simulated system, taking credit to the automatic programmation of the functional specification, with a coupling with a rigid aircraft model
- test of an equipment on a partial test-bench, with input simulation and observation of internal variables (for computers)
- tests on iron bird and flight simulator. The iron bird is a test bench with all the system equipment, installed and powered as on aircraft. The flight simulator is another test bench with an aircraft cockpit, flight controls computers, and coupled with a rigid aircraft model. The iron bird and the flight simulator are coupled for some tests (see ref. 2).
- flight tests, on up to four aircraft, fitted with an "heavy" flight test instrumentation. More than 10000 flight controls parameters are permanently monitored and recorded.

The working method for these tests is twofold:

- a deterministic way, based on a test program, with a test report answering
- a way which takes credit of the daily use of these test facilities for work on other systems, for demonstration, or test engineer and pilot activity. If the behavior of the system is not found satisfactory, a Problem Report is risen, registered and investigated.

6. Significant differences between A320 and A340 flight controls

The A340 is bigger than the A320 with more and larger aerodynamic control surfaces. Therefore, the A340 computers and actuators are different from those of the A320. The functions of the system are similar on both aircraft except for adaptation to suit the flight qualities, the performances and the structure of the A340.

The dependability principles have remained the same from the A320 to the A340. However, methods have been improved. Three examples are detailed in the following design steps:

- system architecture design,
- verification of equipment functional specification,
- production of software.

6.1 Definition of flight control system

The definition of the system requires that a certain number of actuators be allocated to each control surface and a power source and computers to each actuator (this form the system architecture, figure 4 as an example). The writing of such an arrangement implies checking that the system safety objectives are met. A high number of failure combinations, up to several thousand, must therefore be envisaged. A study has been conducted with the aim of automating this process.

It was seen that a tool which could evaluate a high number of failure cases, allowing the use of capacity functions (see ref. 7), would be useful and that the possibility of modelling the static dependencies was not absolutely necessary even though this may sometimes lead to a pessimistic result. This study gave rise to a data processing tool which accepts at input an arrangement of computers, actuators, hydraulic and electrical power sources and also specific events such as simultaneous shutdown of all engines and, therefore, a high number of power sources. The availability of a control surface depends on the availability of a certain number of these resources. This description was made using a fault tree-type support as input to the tool.

The capacity function used allows the aircraft roll controllability to be defined with regards to the degraded state of the flight control system. This controllability can be approached by a function which measures the roll rate available by a linear function of the roll rate of the available control surfaces. It is then possible to divide the degraded states of the system into success or failure states and thus calculate the probability of failure of the system with regards to the target roll controllability.

The tool automatically creates failure combinations and evaluates the availability of the control surfaces and therefore a roll controllability function. It compares the results to the targets. These targets are, on the one hand, the controllability (availability of the pitch control surfaces, available roll rate, etc.) and, on the other hand, the reliability (a controllability target must be met for all failure combinations where probability is greater than a given reliability target). The tool gives the list of failure combinations which do not meet the targets (if any) and gives, for each target controlability, the probability of non-satisfaction. The tool also takes into account a dispatch with one computer failed.

6.2 Verification and validation of functional specifications

Certain functional specification verification activities are performed on data processing tools. For example, the syntax of the specification can be checked automatically. A configuration management tool is also available and used.

The specification is validated mainly by rereading (in particular, during the safety analysis) and by ground or flight tests (see § 4). Our target is validation at earliest possible stage. To achieve this, various simulation tools exist and this because the specifications were written in a formal language making the specification executable.

This makes it possible to simulate, the complete flight control system, computers, actuators, sensors, and aircraft returns (OSIME tool - OSIME stands for Outil de SImulation Multi-Equipement). It is also possible to inject with this tool some stimuli on data which would not be reachable on the real computer. The signals to be observed can be selected arbitrarily and are not limited to the inputs/outputs of a specification sheet. The test scenarios thus generated can be recorded and rerun later on the next version of the specification, for example. A global non-regression test is in place, allowing for each new standard of computer specification, to compare the test results of the previous version, and of the new version. This comparison allows to detect modification errors.

Also, the part of the specification which describes the flight control laws can be simulated in real time (OCAS tool - Outil de Conception Assistée de Spécification) by accepting inputs from a real sidestick controller (in fact, simpler than an aircraft stick), and from the other aircraft controls. The results are provided on a simulated Aircraft Primary Flight Display for global acceptance, and in more detailed forms, for deep analysis.

The OSIME and OCAS tools are coupled to an aerodynamic model of the aircraft.

6.3 Automatic programming

The use of automatic programming tools is becoming widespread. This tendency appeared on the A320 and is being confirmed on the A340 (in particular, the flight control computer "PRIM" is, in part, programmed automatically). Such a tool has as input SAO sheets (see § 3.1), and a library of software packages, one package for each symbol utilized. The automatic programming tool links together the symbols packages.

The use of such tools has a positive impact on safety. An automatic tool ensures that a modification to the specification will be coded without stress even if this modification is to be embodied rapidly (situation encountered during the flight test phase for example). Also, automatic programming, through the use of a formal specification language, allows onboard code from one

aircraft program to be used on another. Note that the functional specification validation tools (simulators) use an automatic programming tool. This tool has parts in common with the automatic programming tool used to generate codes for the flight control computers. This increases the validation power of the simulations.

Note that for dissimilarity reasons, only the "PRIM" computer is coded automatically (the "SEC" being coded manually) and that the PRIM automatic coding tool has two different code translators, one for the control channel and one for the monitoring channel.

7. A320 in service experience

The A320 has accrued around 1.5 million flight hours, with 360 aircraft in service (december 1992), each aircraft is equipped with 2 ELAC, and 3 SEC. Several aircraft have accrued more than 10000 flight hours. During these revenue flights, fault-tolerance mechanisms have been activated, as

- some hardware failures occurred, in a consistent manner with predicted reliability,
- during one flight, both ELAC were lost following an air conditionning failure and the subsequent abnormal temperature rise. It appears that a batch of these computers was fitted with a component whose temperature operating range did not match exactly the specified range.

In all cases, failure detection and reconfiguration was successfull, including the automatic takeover by the SEC in the last case, which justify our use of dissimilarity for availability.In addition, the last problem has been corrected.

To conclude, it is worth noting that the A320 flight controls system has gained good acceptance from airlines and pilots (see ref. 8, and 9), and that procedures for reporting and analysing significant problem detected in airline operations are still active.

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Figure 1.a: conventional flight controls

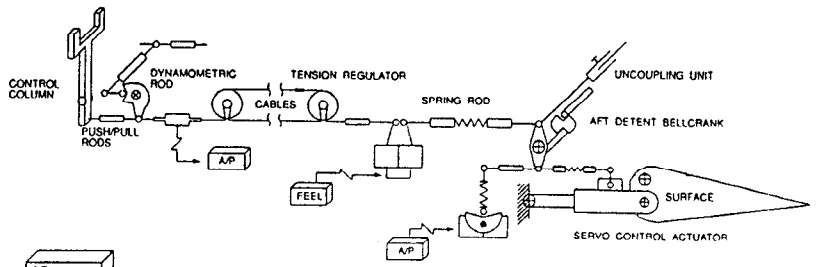
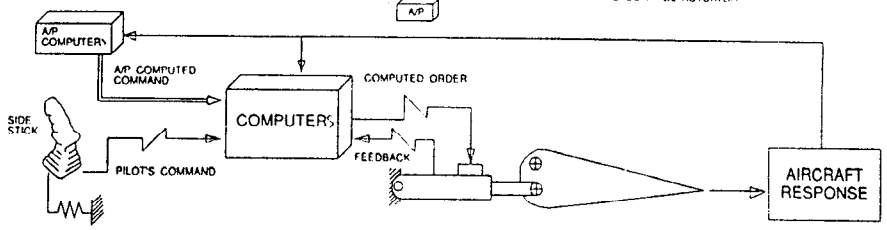


figure 1.b: electrical flight controls



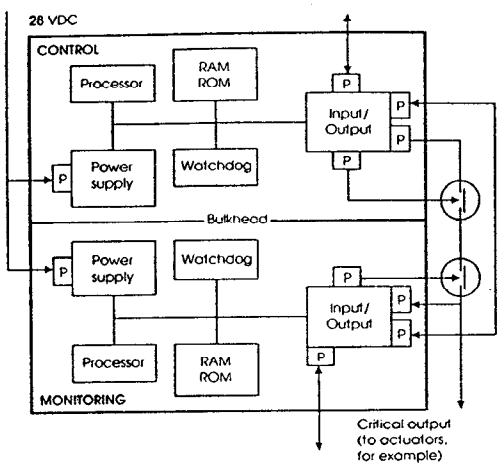


Figure 2: control and monitoring computer

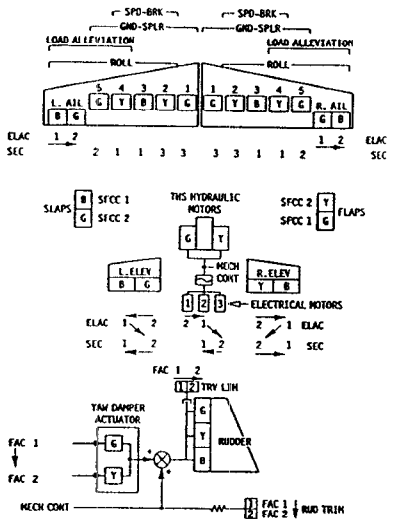


figure 4: A320 flight controls architecture

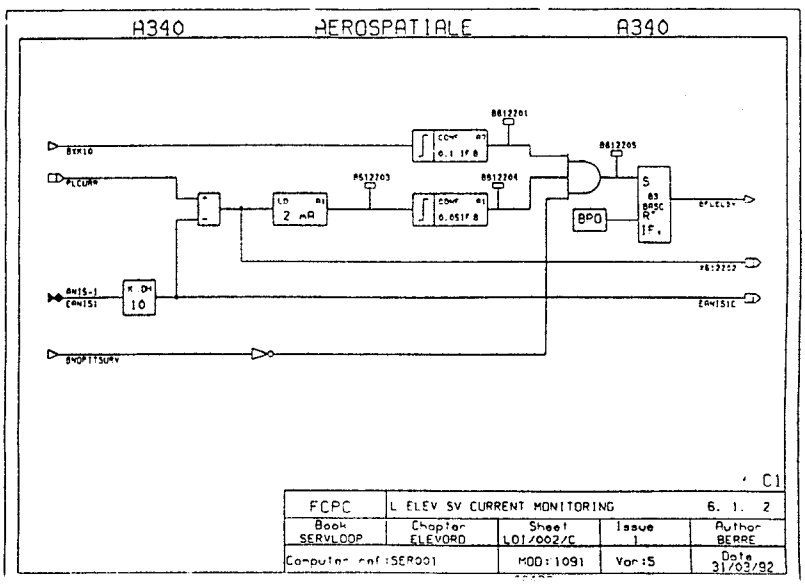


Figure 3: SAO sheet example