FLIGHT TEST DATA ACQUISITION SYSTEM

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ABSTRACT

This paper describes a data acquisition system with integral signal conditioning capability. It is a distributed bus oriented system which greatly reduces the amount of wiring and structural penetrations required in previous systems used for this purpose. The system interfaces with virtually all of the transducer types existing on operational aircraft as well as those typically used for flight testing and proofing such as the strain gauges. It outputs data in digital form to a central unit which combines this data with other aircraft operational parameters for recording on tape or telemetry to the ground.

The system consists of a remote multiplexer (RMUX) which provides the formatting and central processing functions and has provision for 16 plug-in signal conditioning modules. It also has provision for up to 20 external multiplexers (EMUXes) which are designed to service a cluster of like sensors in a local area. EMUX types include bridge, thermocouple, and a highly integrated pressure scanner unit. Signal conditioning and processing functions include input transient protection, variable blocks of gain, analog pre-sample filtering, and precision bandlimiting using digital techniques .

The penalty for moving the acquisition units to remote locations on the aircraft as compared to previously used cabin mounted equipment is a much more severe environment. Temperature extremes and vibration are particularly severe around the engines. Because of the planned use on operational aircraft, provisions to prevent lightning propagation to the cabin are a significant future.

INTRODUCTION

In this paper, we discuss the rationale for developing the Remote Analog/Digital Multiplexer (RMUX) as well as many of its design aspects. The RMUX was developed primarily to support certification testing of new generation commercial jet aircraft. These aircraft with electronic controls and more efficient structures less tolerant of penetrations were prime drivers for the RMUX.

The RMUX is part of the new Boeing Flight Test Data Acquisition System currently being developed Figure 1. The RMUX provides excitation, signal conditioning, bandlimiting pre-sampling filters, multiplexing, digitizing, and digital bandlimited filtering for most transducer and signal types now employed in Flight Test. Several types of plug-in signal conditioning modules have been developed to provide a multitude of RMUX configurations - depending on the immediate testing needs. However, more significant is that the RMUX provides these functions while being installed external to the fuselage and close to high concentrations of transducers on the aircraft for in-flight testing.

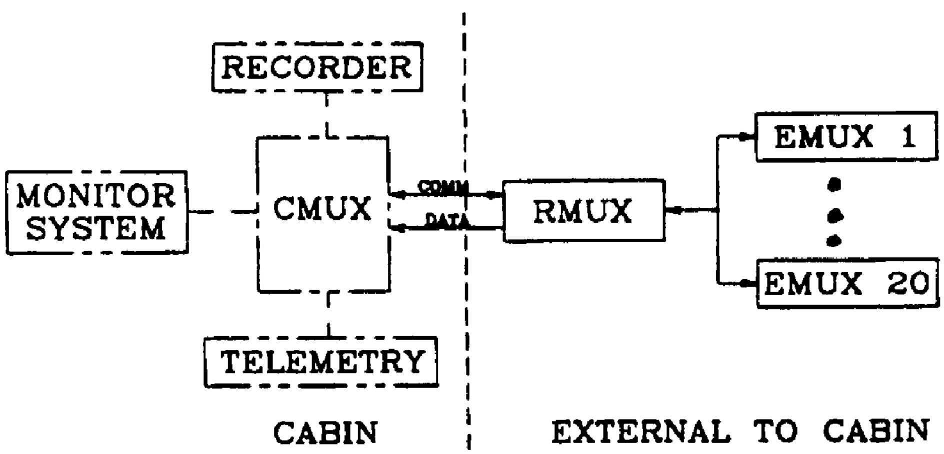

FIGURE 1 - FLIGHT TEST DATA SYSTEM

THE TRANSITION TO THE NEW

Past data acquisition systems have resided in the somewhat "mild" cabin environment where they could service the entire aircraft. Large bundles of transducer cables were routed from the engines, wings, landing gear and tail, to the centralized system in the cabin. In recent years, electronically controlled engines have required electrical isolation in the case of lightning strikes (redundancy was added to prevent multiple failures), so the cabin data acquisition systems had to be split in order to comply. For this reason and the fact that larger numbers of instrumented pickups are more common (larger wire bundles versus less penetrable - more efficient aircraft structures) were drivers to move the common node of serial digitized data out of the cabin and to within close proximity of the empennage transducer locations.

Referring to Figure 2, isolation between engines and cabin is provided by the RMUX's Central Multiplexer (CMUX) interface and again internal to the CMUX. Transducer cables are greatly shortened thus reducing the magnitude of induced noise picked up from aircraft electrical systems. The CMUX interface cable provides both a bi-directional serial communications/control path to the RMUX and a uni-directional high speed digital data path to the CMUX. This cable, capable of operating at lengths up to 300 feet, along with a DC power supply cable now replaces several hundred long transducer cable runs to the fuselage, and has greatly reduced the number and size of structural cable routing penetrations for Flight Test.

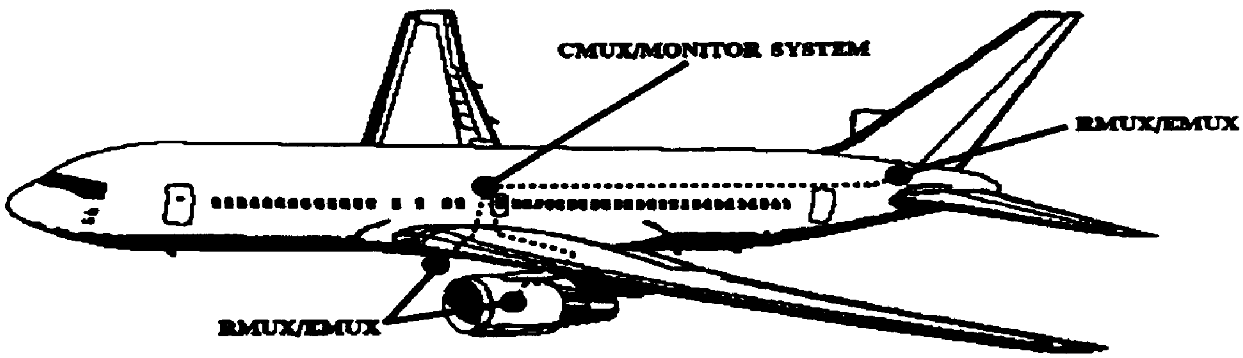

FIGURE 2 - TYPICAL RMUX LOCATIONS

High concentrations of resistance bridge strain, thermocouple temperature and pressure type measurements are common on certification test aircraft. Given the need for RMUX versatility its projected size would not always allow it to be mounted in close proximity to the sensors. To improve this, three External Multiplexers (EMUXes) in a low profile package were developed. They provide signal conditioning, bandlimiting pre-sampling filtering, multiplexing, and digitization for large numbers of measurements with the same transducer types. The EMUXes are controlled by the host RMUX. They are treated much the same as an RMUX internal signal conditioning module, but are mounted separately from the RMUX, receive separate DC power, and communicate with the RMUX over a single high s digital cable. Each EMUX can be located up to 100 feet from the host RMUX, thus providing significant test configuration versatility.

The RMUX and EMUXes are designed to be mounted in areas of minimal access, making system operational visibility, reconfiguration, and troubleshooting difficult to achieve. A significant effort was expended to make the RMUX "system" function as well or better in these areas as the previous system mounted in the cabin. Normal data output to the CMUX provides health voltage, box temperature, and various system status parameters. The bi-directional communications port allows in-depth interrogation into the RMUX/EMUX memory operations along with providing a means to perform reconfiguration of software controllable parameters. System self test reporting and signal conditioning functional tests (bridge shunt calibrations, reference test voltages, and thermal amplifier drift compensation, among others) are performed at the user's request. Down loading of the RMUX sampling format, module signal conditioning type, transducer excitation levels, gains and filter selections occur over this port from the host monitoring system via the CMUX. This provides the flexibility to make major system reconfiguration changes daily without accessing the hardware. Further conditioning type changes are possible via module level jumper reconfigurations or module additions.

MAIN ARCHITECTURE DRIVERS

These items summarize specification requirements which had a major impact on the overall architecture.

- o Format Programmability/Reprogrammability
    - Sample Rate Selection
    - Filter Selection
- o Packetized Output Data Format
- o Programmable Transducer Excitation
- o Gain Programmability
    - Configuration Gains (typically steps of 10)
    - Measurement Gains (binary steps)
- o Offset Management
    - Remove drift offsets (requires ability to apply zero to inputs)
    - Arbitrary zero suppression (Programmed offsets)
- o Serial Data Busses Unit to Unit (Twisted Pair)
- o Highly Flexible RMUX Configuration
    - 16 Plug-in slots
        - Ten Signal Conditioning Types
        - Input Connectorization suitable for all modules (four 100 pin signal input connectors)
        - Mechanical Access for Reconfiguration
- o High Density Specialized External Multiplexers (EMUXes)
        - Low Height Form Factor (No access!?)
        - Dedicated to transducer type
            - Bridge
            - Thermocouple
            - Pressure

- o Configuration Reporting
- o Health Monitoring
- o Fault Isolation Requirement

PERFORMANCE DRIVERS

o	Total Output Data Rate	200Ksps @ 16 bits/sample
	per Channel Sample Rates	5sps to 12.8Ksps
o	Accuracy	0.05% dc - low frequency .1% to .5fc
o	Sample Spacing Tolerance	± 3.5μsec
o	Gain Range	0.25 to 800
o	Input Configuration	Single Ended Differential Balanced Differential Floating
o	Input Impedance	Megohm range with power on or off
o	Noise Rejection	-72 to -80db out of band
o	Operating Temperature Range	-55°C to + 115°C
o	Minimal Cost	

- \- Size
- \- Weight
- \- Monetary
- \- Maintenance

ENVIRONMENTAL DRIVERS

o	Temperature	-55°C to + 115°C
o	Vibration	6 grms
o	Cable Noise	Less severe than old centralized installation (maximum length 100 ft sensor to unit)
o	Size and Weight	Small and light as possible
o	Accessibility	No access in flight except via bus port
o	Power Supply Noise	Small size makes power supply isolation difficult
o	EMI/Lightning	5000V to 200A on bus ports

MAIN DESIGN FEATURES

1. Random Channel Addressing or Sequencing (All data requests originate at the central formatter of an RMUX.)

2. Gain requirements are met by a combination of input circuit set-up configurations over a range of 100:1 and a measurement to measurement programmability over a range of 8:1. This yields a range of 800:1. Jumper programming also allows a gain of 0.25.
3. Digitization is performed at the module level and at each EMUX.
4. Precise bandlimiting is provided by digital filtering techniques. The filtering arithmetic is implemented using digital signal processing hardware.
5. Analog bandlimiting is provided only in the sense that it prevents aliasing when sampled at specified rates.
6. All channels are allocated a 16 bit word size. Initial digitizations are 12 to 15 bit. Subsequent filtering makes data useful to 16 bits.
7. All offsetting or zero suppression is done digitally.

OPERATION SUMMARY

All configurations and the channel and sampling schedules are uploaded by an operator via the bidirectional communications port. Read back information ensures the operator that the system and the requested format are compatible. Built In Test (BIT) features are available to help pin-point or localize the nature of any problem. During flight BIT is useful primarily for giving a "warm feeling" that things are working. At pre-flight BIT is useful in expediting proper system deployment.

At completion of "Boot-up", data collection commences. The "data collector" moves data from addressable modules in the RMUX and EMUXes as demanded by the format. When the data needs processing by the DSP, the raw data is delivered to the DSP then one output sample time later the result is outputted.

RMUX PRINCIPLE FUNCTIONAL BLOCKS

The central or core part of the system resides in the RMUX. It contains the following blocks:

- CMUX Interface
- Data Collector
- Digital Signal Processor
- Central Processing Unit (CPU)
- External Multiplexers (EMUX) Interface

All formatting and timing functions of the system originate in the data collector. It utilizes non-volatile memory (EEPROMs) which is uploaded from an external loader/verifier via the I/O port. A precision clock provides the basis for sample timing functions.

Data signals originate from the plug-in modules of the RMUX or the specialized EMUXes. The Data Collector moves data from these modules to either the output buffer or the DSP for further processing. The DSP provides two kinds of filtering and in the case of thermocouple temperature measurements, conversion to engineering units. Pulse count interval information is inverted to read out as frequency. The choice of filtering or no filtering is optional as directed by the format generated by an external loader/verifier and loaded into non-volatile memory.

The CPU serves primarily housekeeping and initialization functions. It performs the housekeeping functions in the background so as not to interfere with the Data Collector in moving data in a timely manner to meet the format requirements. One of the housekeeping tasks is to monitor the temperature not only of the RMUX itself, but of each EMUX. After a pre-determined temperature change, it raises a flag which calls for a re-zeroing of the input amplifiers. Re-zeroing is performed on command by grounding the amplifier inputs and storing the digitized output for subtraction from subsequent measurements. Initialization tasks of the CPU include set-up of input modules including gain, offsetting, and filtering configurations.

EMUX PARTICULARS

There are three (3) types of EMUXes in the present system. The interface with the RMUX is identical for all three and any future EMUX types would use the same type of interface. In the RMUX, the "EMUX interface" module contains four ports and each port will accommodate any EMUX. A total of 5 such interface modules can be accommodated in the RMUX setting the total number of EMUXes deployable per RMUX at 20. From 320 to 600 signal sources can be serviced if each EMUX is used to its maximum capability. The "Pressure EMUX" is a 16 channel unit while the other two are 30 channel units.

The Bridge EMUX provides set-up selectable excitation to 30 bridges at either 10V, 5V, or 2V. Each excitation source is short circuit proof and independent of the others. The serial interface bus limits the composite interrogation rate of any EMUX to 51.2Ksps. This allows a 1.6Ksps interrogation rate per channel for the Bridge EMUX. This will service the majority of bridge type signal sources. (An 8 channel plug-in module for bridges deployable in RMUX can accommodate sample rates to 12. 7Ksps per channel.) Individual channel amplifiers and bandlimiting filters are optimized for output sampling @ 1.6Ksps. At lower sample rates, there is a danger of introducing aliasing errors because the bandlimiting filters are fixed.

There are three distinctive features of the Thermocouple EMUX (TC EMUX) that merit mention. First of all it provides cold junction compensation for chromel alumel type thermocouples. It takes the form of an isothermal block whose temperature is measured with a platinum sensor and reported to the RMUX DSP for conversion to engineering units. A second and demanding feature allows this EMUX to tie into aircraft operational temperature sensors. There must not be any loading or disturbance introduced whether EMUX power is on or off, or if there is a failure in the input circuitry. Special high impedance with power off switches are used to ensure this. The third distinctive feature of the TC EMUX is that the input thermocouple sensors can be completely floating relative signal ground or chassis.

The Pressure EMUX (P EMUX) is unique in that it accepts signals in the form of pressure via pneumatic tubes. Semiconductor strain bridges are used to convert differential pressures to electrical signals. A system of ports and valves allows zeroing of pressure inputs and the application of reference pressures. The outputs of the sensor bridges are amplified and conditioned before being multiplexed into a single A/D converter. The interface to the RMUX is identical to the other EMUXes.

BANDLIMITING FILTERING

One of the unique features of the system involves the approach to bandlimiting filtering. An analysis of the performance desired or required for bandlimiting identified severe problems with purely classical analog techniques.

The operating temperature range causes the most difficulty. A combination analog/digital filtering approach was adopted. Analog filters designed to support relatively high input sampling rates are much simpler than filters that would be suitable for final bandlimiting. A multiplicity of filter cut-off frequencies and attendant output sample rates are provided using digital filtering followed by decimation . The inputs are over sampled relative to the final output rates by as much as 80 to 1 compensate for the subsequent decimation. Analog pre-sampling filters with cut-off frequencies in the l00Hz to 200Hz range are now adequate. The filter selection tree designed to support the signals emanating from the Bridge EMUX illustrates the arrangement. See Figure 3. Each channel can be independently programmed as to output sample rate and filter cut-off frequency according to the available paths on the tree. When no digital filtering is desired, the output rates and input rates coincide but still limited to one of the output rates shown.

The basic DSP module contains two DSP chips along with supporting memory. Sets of pre-determined coefficients stored in non-volatile memory are selected as part of the formatting instructions. Finite Impulse Response (FIR) filters are the main types used. Equivalent "N"s or tap lengths up to 1024 can be selected. As shown, several choices of Butterworth approximations are available. Infinite Impulse Response (IIR) digital techniques are used for these 4 pole filters.

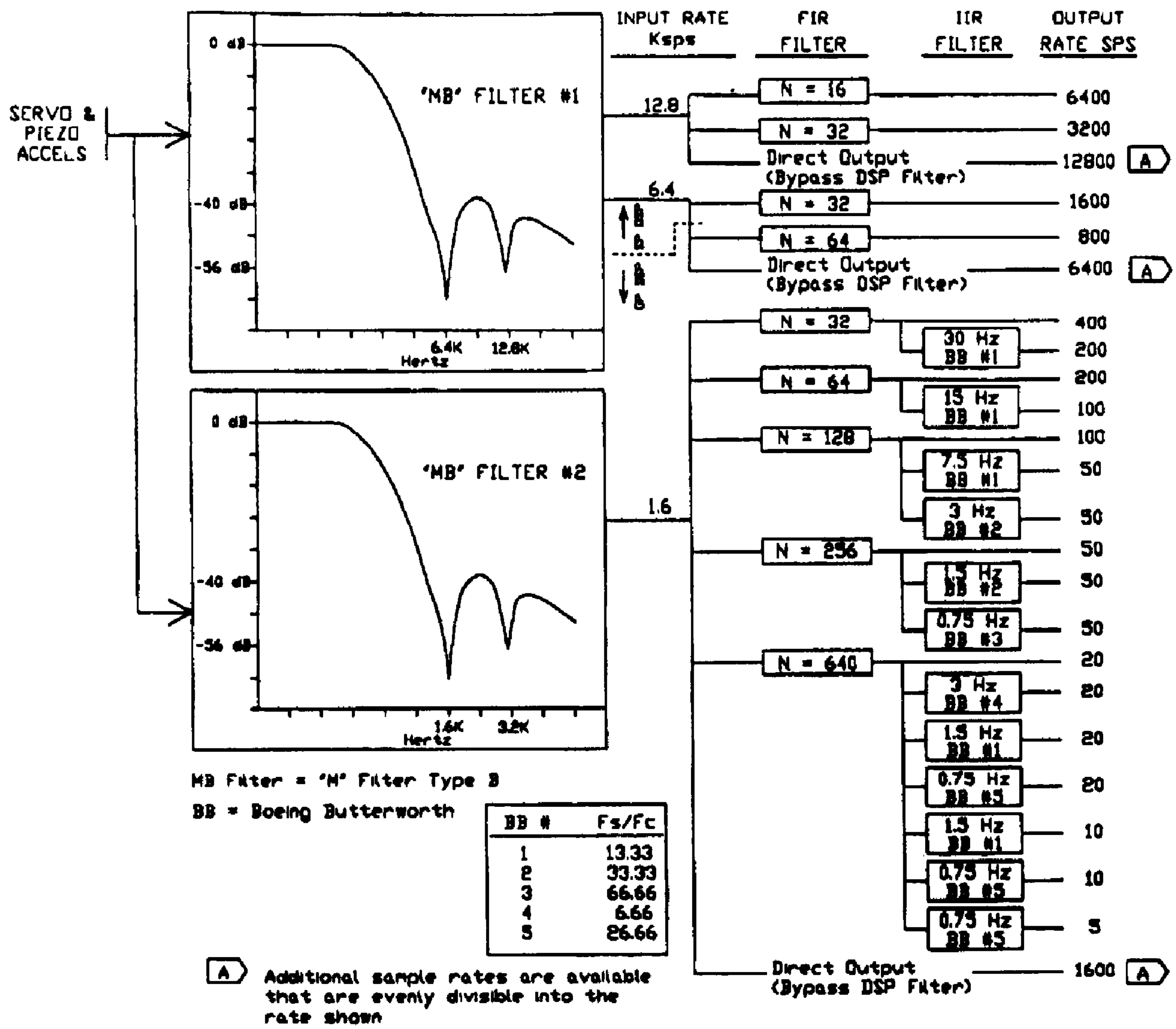

FIGURE 3 - TYPICAL FILTER TREE

Additional DSP modules can be plugged in at the expense of up to two of the 16 plug-in slots available for input modules. One DSP module can handle the filtering for 32 to 256 channels depending on sample rates .

A performance bench mark of the system is its ability to extract low-level low frequency (5 to 10Hz) wow and flutter signals from accelerometers mounted near the engines. High amplitude high frequency turbine blade induced signals can be as much as 60 db larger in amplitude than the low frequency signals. To this end, the number sizes (number of bits) maintained in the filter arithmetic computations needs to be held at least at the 24 bit level. Samples digitized to 15 bits and coefficients of 16 bits lead to 31 bit partial products. Only the 7 LSBs of these partial products can be ignored. The dynamic range of the filters exceeds 80db.

SAMPLE TIMING AND LATENCY CONSIDERATIONS

One of the overall performance requirements Boeing levied on the system was to be able to take any output sample and identify when in time the sample was taken. Since each output word time can be as short as 5 µsec, sample acquisition has to start prior to when the data is needed for output. Simply reading the last sample taken from memory at the input module for a particular channel as not satisfactory. Sampling had to be synchronized to the output format requirements. The system is designed to perform the sampling and digitization "just in time" for the Data Collector to move the result to the output. Some module types need a "warning" of 10 µsec for this to happen, others need in excess of 100 µsec. Variable resistance sensors such as platinum resistance thermometers, for example, are read out by applying a constant current and reading the resultant voltage. The cable capacitance connecting the module to the sensor must be charged. Settling to sufficient accuracy can require up to 100 µsec. To meet the "just in time" criteria for a variety of signal types requires then module specific timing instructions.

Because the EMUX/RMUX interface is over serial busses, additional timing considerations are involved. There is no restriction in the overall format as to data source whether EMUX or RMUX for any particular word. For EMUX data, "just in time" means that the requests for data are initiated early enough to compensate for the delays going out and back to an EMUX with a request and a reply.

CONCLUSION

The move to remote data acquisition was a very challenging and complicated one. In short, the entire capability of the previous Flight Test data acquisition system, some 15 years old, was recreated in ruggedized form, with no compromise in functionality or accuracy. Advances in hardware technology, innovative design techniques, and the addition of software control have made this possible. However, the concentrated efforts of a co-development team, conscientious to the finest detail of possible operational scenarios have made this project work.

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