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Title: **Developments in Digital Data Acquisition/Analysis System Technology for Large-Scale, Structural-Dynamic Testing Facilities**

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This paper reviews the philosophy of large-data-acquisition-system design as it has evolved over the past 20 years and discusses recent developments in applicable hardware and software tools. PIRANHA, a 320-channel system that embodies many of the features discussed and takes advantage of the new technologies, is described.

Introduction

Structural-dynamic characterization, qualification, and acceptance testing of aerospace structures demands the highest performance, large-scale, data acquisition and analysis systems. These systems gather, store, and analyze data from hundreds of channels whose bandwidth is measured in kilohertz. Until recently, the capabilities of these systems have been limited by available hardware resources. In the past few years, new hardware and software concepts have emerged that allow changing the criteria for system design from available technology to the requirements of the laboratory.

Philosophy

In the aerospace industry, a "large-scale" test is normally a high-visibility, time-critical, experiment performed on very expensive equipment. To add to the challenge, the tests often are scheduled near the end of a program where delays are most visible and the pressure to perform quickly is most intense. The saving (or loss) of a few hours can affect program costs significantly. The tests must go smoothly and be completed in a minimum amount of time. System factors that contribute to program success include:

- Reliability: Lost, incorrect, or inadequate data or test delays because of hardware failure are not acceptable.
- Grace under fire: The operators of these machines are normally under intense pressure. The system must help the operator avoid bad decisions and harmful actions. It must be flexible to allow test and analysis variances but it should be "pre-programmable" in a way that minimizes decisions that must be made during the test.
- High tolerance for misjudgments in expected response: A response ten times as large or 10% of expected should be handled gracefully and accurately.
- Rapid data "turn-around": Facilities to process the data quickly are required to allow timely recognition and resolution of testing errors/discrepancies and/or specimen failures in the presence of potentially-overwhelming amounts of information.
- Automatic hardware setup and health monitoring: No intervention should be required to make the necessary adjustments and assure that the system is functioning correctly.
- Instrumentation-installation "assistance": Efficient tools for installing and verifying the performance of response measurement devices are required.
- Flexibility/Modularity: The system should be capable of being configured to support a wide variety of experiments. The full system should also be able to be broken down into stand-alone subsystems to perform multiple small tests.

These attributes speak to the performance of the system as perceived by management and are the kind of words that are necessary to promote the procurement of a new system. Beyond that, technical requirements and hardware and software specifications must be established. Critical parameters, and available capabilities, include:

- Signal Bandwidth[1]

  The frequency range of the data to be analyzed is the most fundamental characterization parameter in any measurement system. All of the components in the transducer-to-storage data path must be capable of supporting the frequency range, and consequent data rates, required. In the structural-dynamics world the most demanding requirement is normally in pyrotechnic testing where shock response spectrum (SRS) analysis to 10KHz (which translates to a data bandwidth of at least 15KHz) is the usual requirement (Reference 1). In a few cases higher frequencies may be required (Reference 2).

  With recently developed hardware, a bandwidth of 45KHz is commonly available for large-channel-count systems. 90KHz is offered by a few vendors and will be the norm by the year 1999.

1 Note that bandwidth is used as the critical parameter rather than sample rate. The sample rate required is a complex function of the bandwidth, the system hardware characteristics, and the allowed level of error from aliasing effects. For the hardware configuration discussed below, the sample rate can be as small as the data bandwidth multiplied by 2.2.

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- Test Duration

  The system must acquire data for the duration of the experiment. In addition, it is often desirable to monitor the test throughout the whole period that the excitation system is energized.

  The product of the number of channels, the sample rate, and the duration defines the quantity of data that must be stored (and reduced). For large systems, this often amounts to billions of samples.

  Modern hardware makes it reasonable to store ten or twenty minutes of data with a bandwidth of 45KHz for hundreds of channels. Analysis and inspection of a complete data set of this size is an enormous task but, for most structural-dynamic tests, only a relatively-small part must be reduced. Tools to select the subset and rapid analysis of that part are required.

- Accuracy

  The system (exclusive of the transducer) should be accurate to within 1% over the measurement frequency range. This requires a very stable system and analytical, post-test data correction (Reference 3).

- Number of Channels

  The number of measurements to be made is the prime criterion of whether a test qualifies as "large-scale". Adequate representation of the motion of a complex structure normally requires measurement at several hundred points. This may be done via one of two strategies:

  1) Acquire a relatively-small number of channels in multiple passes. Using this strategy, a 64-channel data acquisition system could measure the motion of 256 channels in 4 passes.

     This approach minimizes the up-front cost of the measurement equipment but requires the behavior of the specimen to remain constant, subjects it to more loading cycles, and requires more time to complete. It is normally only acceptable in situations where there is relatively-little time pressure and the excitation levels are low. Modal testing is a possible application.

  2) Acquire all of the channels simultaneously. This alternative:
     - Minimizes specimen exposure and wear and tear.
     - Reduces the test/facility time.
     - Resolves repeatability questions.
     - Reduces setup and patching errors.
     - Simplifies bookkeeping.

  For testing of complex structures this approach normally reduces test costs and produces significant improvements in the reliability and robustness of results.

  Balancing these technical issues and run-time cost considerations is the "up-front" price of the data acquisition system. Depending on the measurement type and hardware selected, the incremental cost of each channel will be between $500 and $2,500.

  The economics of system sizing is straightforward. For the applications that are under consideration here, where an hour of testing may cost $10,000, one hour saved pays for ten, $1,000 channels. When compared to its predecessors, the system described below saves over six hours in the turnaround of a 256-channel test run. Its high channel count is very quickly justified.

  Modern testing facilities with systems capable of acquiring over 200 channels with audio-frequency bandwidth are common and the demand for up to 1024 channels is growing. These larger systems are on the near horizon.

- Measurement/Transducer Type

  The signal conditioning that converts the electrical output of the measurement transducer to the voltage required by the analog-to-digital converter has always been the most difficult and expensive part of a large data acquisition system. Typically, structural-dynamic-measurement systems deal with one or more of the following:

  - Piezoelectric charge-to-voltage conversion and amplification.
  - Piezoelectric/Internal Electronic (IE) excitation, coupling, and amplification.
  - Voltage with a wide range of full-scale values.
  - Wheatstone bridge completion, excitation, balance, and amplification.
  - A variety of application-unique conditioning methods such as thermocouple linearization and amplification.

  These operations are so fundamentally different that no "universal" solution has been invented. At present, the best solution is a master conditioning system with plug-in modules that are specifically designed for each transducer type. This approach is inconvenient and expensive and a better solution

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is badly needed.

For large systems, the signal conditioning system (in conjunction with other components) should provide:

- A high dynamic range (signal-to-noise ratio) that allows conservative selection of gain ranges.
- Automatic “adjustment” (such as bridge balance or AC/DC coupling) as required for the device. The system should provide full diagnostics and logging of anomalies (such as failure to achieve bridge balance).
- Programmable range, set by definition of expected responses (in engineering units).
- Automatic transducer connection verification (such as bias-voltage checks on “internal-electronic” piezoelectric transducers).
- Automatic diagnostic/calibration verification by known-signal injection. Performance over the full frequency range of interest should be verified.
- Detection of saturation/overload at the system input (before any filtering is performed). Anomalies should be displayed and logged, and the acquired data should be tagged.

A few vendors offer systems that satisfy these capabilities. The technology is there for all to implement.

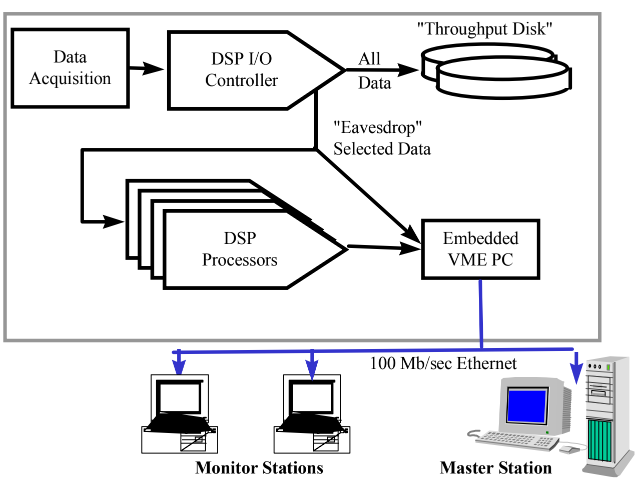

Figure 1 DSP Data Stream Management

New Tools and “Off-the-shelf” Technologies

An important goal of any system development task is to provide an adequate system at a minimum cost. Components and tools of the highest level, consistent with the flexibility required, are usually the most “efficient”. Use of an available hardware subsystem is more cost effective than building one from lesser components. In software, using a mature development product with a well-evolved “toolbox” is far cheaper than developing the functions yourself. To this end, the Commercial-off-the-Shelf (COTS) market offers an ever-growing family of hardware and software products that reduce the need for a developer to construct his/her own capabilities. In fact, many of the components of a modern, large-scale, data acquisition system can be bought at your local computer store.

The most important new tools and technologies that help the system developer produce “better, faster, cheaper” systems are:

- The Sigma-delta ADC

  The Sigma-Delta (SD) acquisition concept is the most significant advance in digital, audio-frequency data acquisition technology in the past 20 years. These systems, originally developed for the commercial audio industry and found in all compact-disk recorders and players, offer superior accuracy and low signal distortion at a fraction of the price of conventional ADC systems. The concept of SD, though complex in implementation, is relatively simple in concept. The primary “secret” is that a sigma-delta system “over-samples” the data at a speed many times greater (typically 256) than the desired sample rate. The converter quantizes the signal with a simple, 1-bit comparator, and digitally filters and decimates the sampled signal to yield the desired resolution and sample rate.

  This approach provides four fundamental advantages when compared to conventional ADC methodologies. First, it eliminates the need for expensive, analog anti-aliasing filters. While alias protection is still required, a simple one-pole RC network is adequate because of the SD’s high sample ratio (sample rate/desired bandwidth). Second, the low-pass filtering performed in the digital calculations yields characteristics that are far superior to analog filters. Aliasing errors are effectively eliminated and, when properly implemented, these devices provide 92 dB of useful signal dynamic range. Third, the filter characteristic provides essentially perfect pass-band

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characteristics with magnitude errors less that 0.1% and constant delay of all frequency components. Last, the devices are inexpensive and are implemented in an ADC-per-channel architecture, eliminating the problems associated with multiplexed acquisition systems.

- High-Performance "Personal Computers"

  Second only in importance to the SD converter for the systems under discussion is the (r)evolution of high-performance "personal computers". These machines, currently led by machines based on the Intel Pentium family, are proving to be excellent number crunchers, challenging, and in the system described below, exceeding, the performance of their conventional workstation brethren. They do this at a much-lower cost while offering the capability of running "main-stream" software programs for auxiliary tasks.

  When combined with high-performance, "hotbox" systems based on VME or VXI architectures, "personal computers" offer a very efficient combination of ease-of- use, performance, and low cost to the large-scale system developer.

- Data Stream Management Systems

  Performance of VME and VXI based data acquisition sub-systems is largely due to digital signal processing (DSP) devices. These are powerful, independent, computing devices that are specialized to perform arithmetic calculations and manage streams of data. For the systems under discussion, their most important function is to "hose" data streams between devices such as A/D converters and disks. The primary destination of the data stream is a high bandwidth recording device such as a SCSI disk. The streams can also be routed to other DSPs for further run-time processing and then to display systems via a network as shown in Figure 1.

- High-Speed networks

  The concept of data streams combined with the ability to shuttle data to numerous system locations is enabled by high-bandwidth, commercially-available networks. One-hundred-million-bit-per-second transmission rates are standard fare and provide the data-transfer capabilities required for today's systems. A ten-fold increase in speed is not far off.

- High-Level Programming Environments

  From the cost standpoint, modern software tools may be the most important development. New graphical, object-oriented languages are proving to produce robust, high-performance systems at a fraction of the cost of the conventional (C or Fortran) programming approach (Reference 4).

PIRANHA

The following paragraphs describe the new Lockheed Martin Missile and Space (LMMS) PIRANHA system that incorporates many of these features.

During the past 18 years LMMS's Computer Aided Testing Systems (CATS) group has built a variety of data acquisition/analysis systems to support a variety of structural-dynamic testing application. The ARDVARC system, which was the first of a family of multi-million-sample-per-second machines, was built in 1982 for high-level acoustic testing (Reference 5). This machine "spawned" a large number of DEC VAX-based machines that were built until 1995 when that technology stagnated. At that time, the group started development of a new hardware/software family based on Intel "PC" computers running National Instruments LabVIEW software tools. The system described here is the largest and fastest of these.

PIRANHA (Figure 2) was developed for use in the spacecraft mechanical tests, supporting large-scale sine/random vibration, high-level acoustic, and pyro-shock experiments in LMMS's new Commercial Spacecraft facility in Sunnyvale California.

Figure 2 The Piranha System

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Basic capabilities of the system are:

- Number of channels: 320 (Five 64-channel modules operating independently or in concert)
- Bandwidth: 45KHz
- Data Storage: Complete time history.
- Recording Duration: 10 minutes: All channels at full bandwidth
- Run Time Calculation/Display: Time History, Sine Response, 1/Nth Octave, Power Spectral Density (Display on any Workstation)
- Signal Conditioning: “Internal Electronic” and Voltage (Single-ended or Differential)
  Fully automated setup with run-time saturation detection and logging
- Data Post Processing: Time History
  Sine Response (Tracking Filtered Complex or Magnitude)
  1/Nth-Octave: Sound Pressure Level (SPL)
  Power Spectral Density (PSD)
  “Narrow-band” Power Spectral Density (PSD)
  Shock Response Spectra
  Transfer Function, Coherence...
- Data Processing/Archive Duration: Processing and archive for a 320-channel test is completed within 1/2 hour

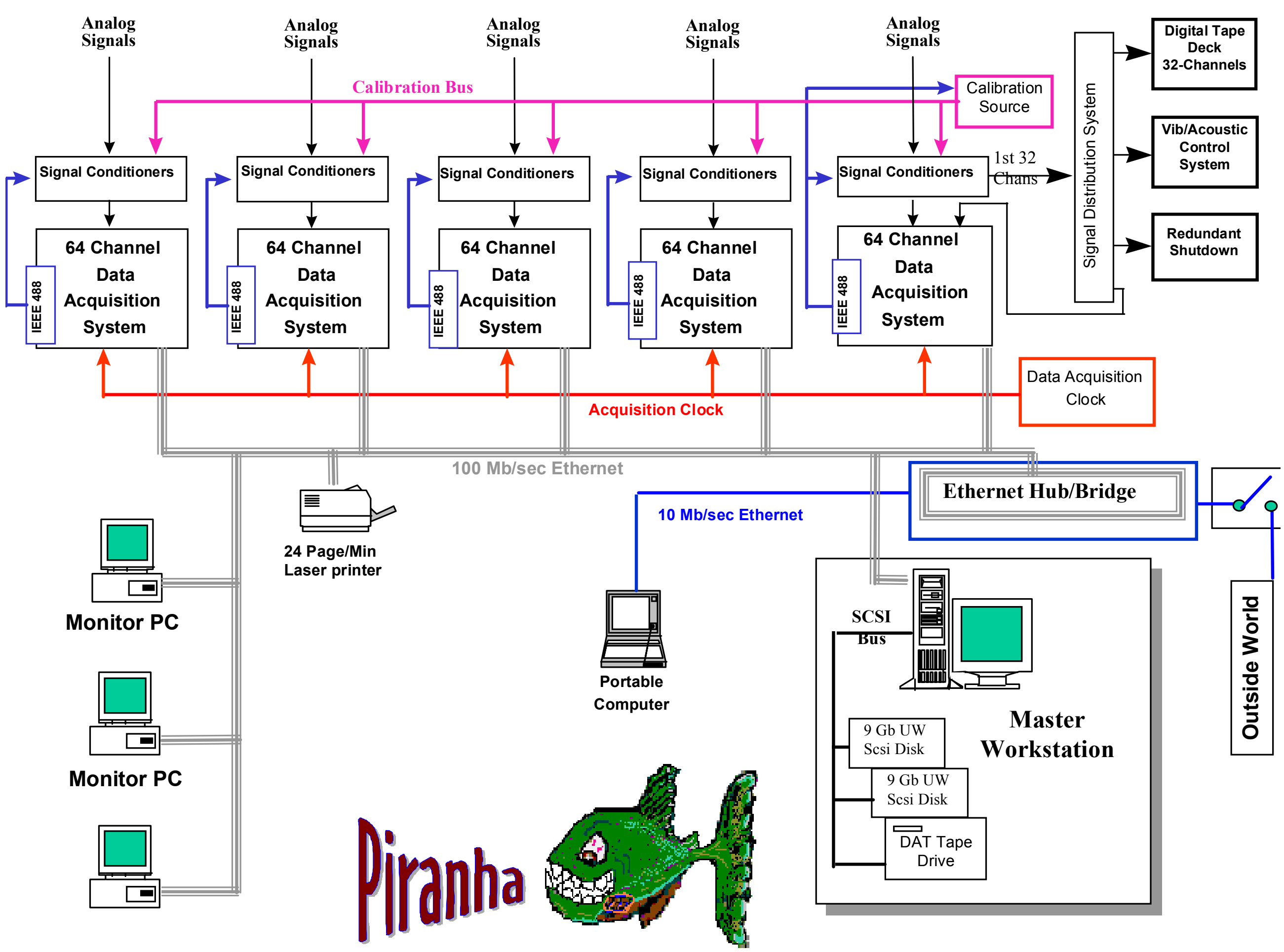

Figure 3 PIRANHA System Schematic

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System Architecture

The PIRANHA hardware system (Figure 3) is made up of:

- Four PC “Workstations”. One is designated as “master” and three are designated as “monitors” during data acquisition. At other times any of the workstations may be used for test definition and/or data reduction. One of the stations is equipped with a large disk-storage system and is designated the “disk farm”. In other respects, the workstations are identical.

  During data acquisition, the “Master Workstation” serves as the controller for the acquisition system. It acts as a “traffic cop”, queuing commands to the acquisition modules and continually verifies the status and general health of the system. The monitor stations can access and display data from any channel that is being acquired.
- Five 64-channel “Data Stations” that are configured as nodes on a high speed network. These modules acquire and store the data, provide data eavesdropping, and perform run-time calculations. They can operate independently as 64-channel systems, or in concert as a fully-integrated system. Additional data stations can be added to increase the channel count without affecting individual-channel performance. Three wires, that carry the network, calibration, and acquisition-clock signals, are the only connections between the data stations. They are connected to the workstations by the 100 Mb/second network.
- Peripheral hardware, such as the system master clock and printers.

Information and Data Flow

Figure 4 cartoons the information flow through the system.

The first step is test setup/definition that is performed by the Test Manager system. This software system includes a multiple-tier data base and a variety of utilities that allow the Test-Definition Database to be loaded manually or via externally-generated (Excel) files. All testing parameters, and much of the post-processing operations, are defined here.

At “run time” the parameters from the Test-Definition Database are downloaded to the Data Stations and diagnostics are performed. The operator controls the data-acquisition operations, such as acquisition start and stop, at the Master Workstation. The Data Stations acquire and store all of the data and “eavesdrop” blocks of data which are passed directly to network-accessible data buffers (time-history for all channels) or to DSP processors (1/3 octave, PSD ... for selected channels). The master and monitor stations can access any of the eavesdropped data sets. They display the DSP processor results from the preselected channels, or individual-channel data displayed as time histories, or locally-calculated spectra.

At the conclusion of the test, the data is transferred from the raw data files on the Data Stations to “CATS files[2]” on the “Data Server” Workstation. From there, they are analyzed in 1/N-octave, narrow-band, sine, or shock response spectra format by any of the workstations. Using a 200 MHz “Pentium Pro”, data extraction, analysis, and plotting of a 320-channel test is completed in less than 30 minutes.

Conclusions

The capabilities of systems used for large-scale, structural-dynamic, tests are no longer limited by the performance of available hardware. Technologies introduced in the past few years allow the construction of systems using “commercial-off-the-shelf” components that satisfy the needs of almost any experiment in the structural-dynamic environment-simulation arena.

The PIRANHA system described is an example of this new generation of systems. This 320-channel machine satisfies the requirements of vibration, acoustic, and pyroshock testing and has demonstrated sufficient cost saving in its first few tests to justify its construction.

[2] CATS files are fully-annotated data sets. The format is “file-per-channel” and each file includes an ASCII header that fully describes the pedigree of the data set followed by the data in binary form.

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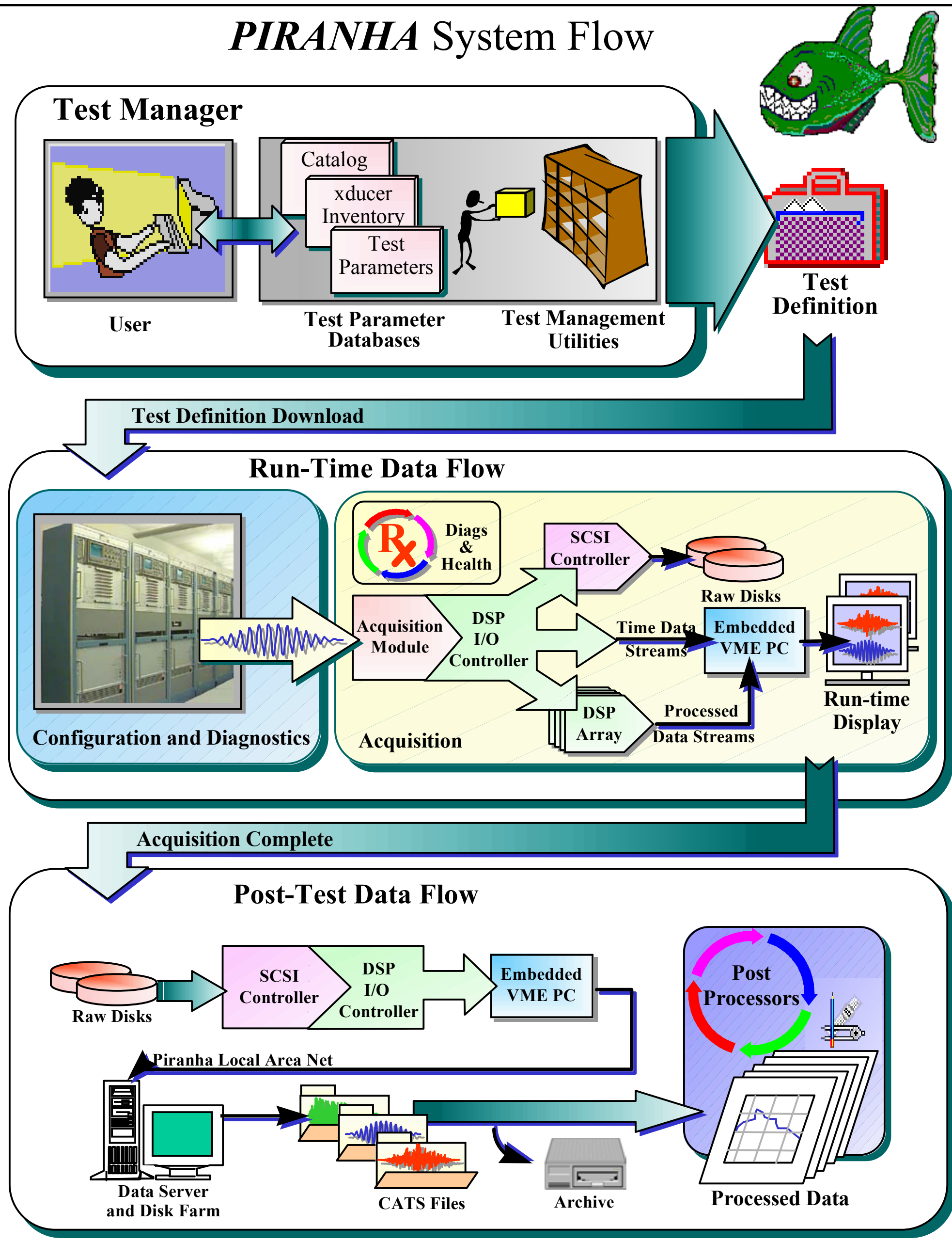

Figure 4
Information Flow

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