Integrating COTS VXI Hardware and Software for the Marine Corps Third Echelon Test System

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Abstract *- This paper presents an overview of the Marine Corps' new Third Echelon Test System (TETS) and describes the work done by ManTech and Teradyne to integrate a standard-based tester able to withstand the unique challenges of the Marine Corps' environment.*

The focus of the paper is on the integration efforts by ManTech and Teradyne in the critical areas of power and cooling design, subject to the system constraints of size, weight, and operating environment. It details other aspects of the integration effort, including tradeoffs in component selection, hardware integration, and mechanical design for a ruggedized environment. The paper will also discuss how the use of standards such as VXI facilitated the integration of a large number of components from a variety of suppliers.

Power and cooling design will be explored at the system level, along with a more focused look at the power and cooling requirements for the TETS digital subsystem. The paper also describes the rigorous testing environment that was part of the system evaluation process.

The conclusion summarizes the challenges of integrating COTS test hardware and software while adhering to the strict require-ments of the target environment, and describe power and cooling techniques that can be applied in a variety of system integration applications.

I. INTRODUCTION

The United States Marine Corps, in the specification of their Third Echelon Test System (TETS), required the use of commercial-off-the-shelf (COTS) equipment to realize the benefits of higher reliability and lower acquisition costs. At the same time, the Marine Corps intended TETS to survive in harsh environments during operation and transport at the forward edge of the battlefield. The combination of COTS and the Marine Corps operating environment represented some unique challenges in the development of TETS.

ManTech responded to this challenge with a VXI-based architecture that exploited the high performance and lightweight attributes of instrument on a card technology. VXI has proven to serve these purposes, but must be given additional levels of protection to withstand the environmental extremes.

The issues involved in designing a test system that ensures reliable operation of COTS equipment in harsh environments were focused on three key areas: system cooling, power distribution, and ruggedized design to withstand shock and vibration.

II. SYSTEM ARCHITECTURE OVERVIEW

The TETS system consists of two VXI chassis of instrumentation controlled by a ruggedized laptop PC running Windows NT. The core configuration includes 192 channels of Teradyne M910 digital, along with a digital multimeter, counter/timer, digitizing oscilloscope, function generator, arbitrary waveform generator, and DC, low-frequency, and medium-frequency switching. The core configuration also includes 10 programmable DC power supplies to power the Unit Under Test (UUT). The RF option adds to the core configuration an RF source, counter, measurement analyzer, power meter, and RF switching. The TETS system, including the RF option, is shown in Figure 1 below.

Figure 1: TETS system

III. SYSTEM COOLING INTEGRATION

In addition to the demanding environmental operating conditions specified by the Marine Corps, several design constraints were placed on the VXI chassis:

1. It must provide greater than 50W of cooling air per slot, with no more than a 10°C temperature rise per slot.
2. It must provide a filtered, positive-pressure, forced-air cooling system.
3. It must be in compliance with IEEE-STD-1155-1992 for C sized chassis.

These three specifications are normal expectations of any COTS VXI chassis and therefore did not present a challenge by themselves. However, when coupled with the constraints of size and weight and the demands of the target operating environment, these specifications did not fully describe the instrument chassis performance.

The VXI specification does not set forth any minimum amount of guaranteed airflow, thereby making it the integrator's responsibility to ensure that the chassis provides enough airflow to sufficiently cool the instrumentation. The VXI specification does, however, provide for a standardized description of individual manufacturers' airflow requirements for modules, and capabilities for the chassis. The modules have a required amount of air, usually expressed in Liters/Second, and a resistance to airflow, usually expressed as a pressure drop in mmH_2O. The chassis have a graph of the performance of the worst slot that displays pressure vs. airflow. The module's performance points must be plotted on the chassis graph to determine if adequate cooling is available.

The HP chassis depicted in Figure 2 was chosen as the host for all VXI instrumentation in TETS. It provided a good airflow scheme, but could not guarantee that enough air would reach the four M910 modules. The air intake is located at the bottom rear of the chassis with air being forced under the modules then up and out the top of the chassis. The chassis provided strategically placed vanes to vector the air, as well as a metered plenum design to ensure even airflow from slot to slot and front to back.

To make substantial gains in the chassis airflow, a change of fans was required. The fans chosen were slightly larger and operated on 24V instead of 12V. At nominal operating voltage, they provided 50% more air at similar pressure levels with an increase in the total pressure available.

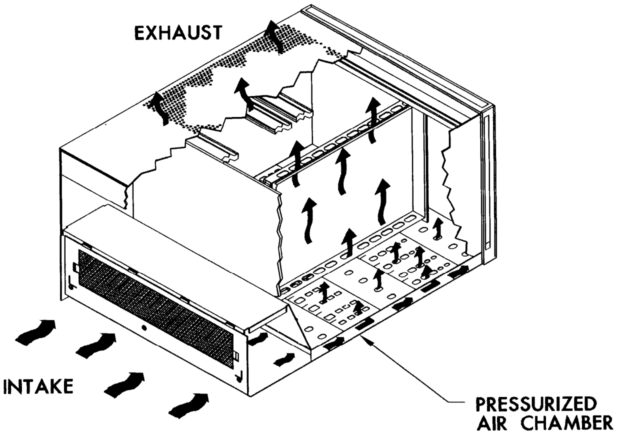
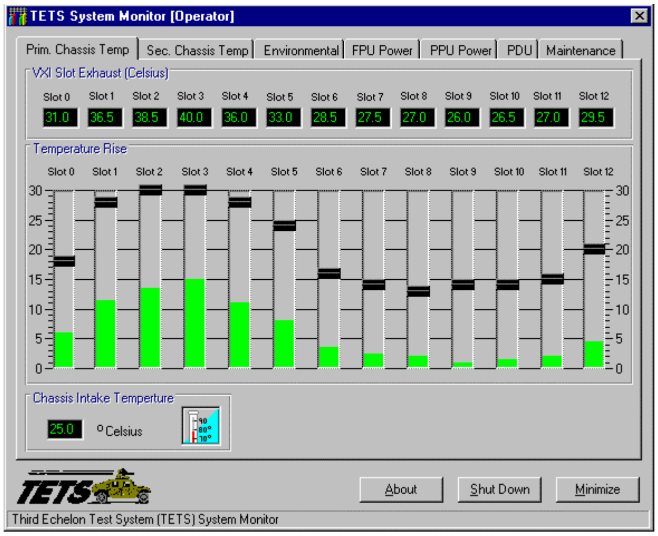


Figure 2: Air intake diagram of TETS chassis

The fans were controlled by a variable-speed fan algorithm that is capable of increasing the fan speed to 33% above the nominal while remaining within the fan's operating range. This provided an extra 33% volume of air on top of the aforementioned 50% gain. The HP chassis's metering plenum, however, delivered all of the extra air equally to all slots within the chassis. In order to deliver the extra air to the M910 modules where it was needed, the metered plenum was modified to match the intake area of the M910. This gave the M910 slots an advantage over the other slots in the chassis as the plenum was no longer providing any resistance to their airflow.



VXI Slot Exhaust (Celsius)

Slot 0	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6	Slot 7	Slot 8	Slot 9	Slot 10	Slot 11	Slot 12
31.0	36.5	38.5	40.0	36.0	33.0	28.5	27.5	27.0	26.0	26.5	27.0	29.5

Chassis Intake Temperture: 25.0 °Celsius

Third Echelon Test System (TETS) System Monitor

Figure 3: Temperature monitoring software

The minimum operating temperature specified by the Marine Corps was -10°C, which presented a problem as most COTS VXI modules are only specified to operate down to 0°C. This problem was overcome with the addition of heaters to the HP chassis. Each chassis is equipped with two heaters that operate independently, one enabled for low heat and both enabled for high heat. Another addition to the chassis was the ability to monitor temperature rise on a slot by slot basis. This information was passed to the TETS system monitoring software, which could then display real time temperature information in graphical form to the system operator or maintainer. A screen shot of the temperature monitoring software is shown in Figure 3. In addition to providing a comprehensive view into how the system is operating, this software also serves to control the environment in which it operates. Based on the temperature feedback, the software can increase or decrease fan speed and enable or disable the heaters. Since most specifications for VXI instruments are based on a 25°C operating temperature, it is desirable to operate them as close to 25°C as possible to achieve the highest degree of accuracy. The system monitoring software was designed to seek this optimum temperature by adjusting fan speed and heater operation. If at any time a module exceeded a 10°C temperature rise from intake to exhaust, the fans will abandon the optimum temperature regulation and increase the airflow to maintain a rise of less than 10°C for reliability purposes.

M910 Cooling Design

The thermal design considerations for Teradyne's M910 digital channel card required diligent engineering analysis to ensure proper cooling. The M910 channel card consists of a main board and a companion board. There are 16 custom ASICs that provide the pin electronics on the channel card. The main board has 4 of the pin electronics ASICs and the companion board has the remaining 12. Heat removal from the ASIC was facilitated by the use of a small-pin fin heat sink developed by Teradyne, as shown in Figure 4. Additionally, careful consideration was given to the component placement of the ASICS to maximize the efficiency of the heat sink. The layout alternatives are shown in figure 5.

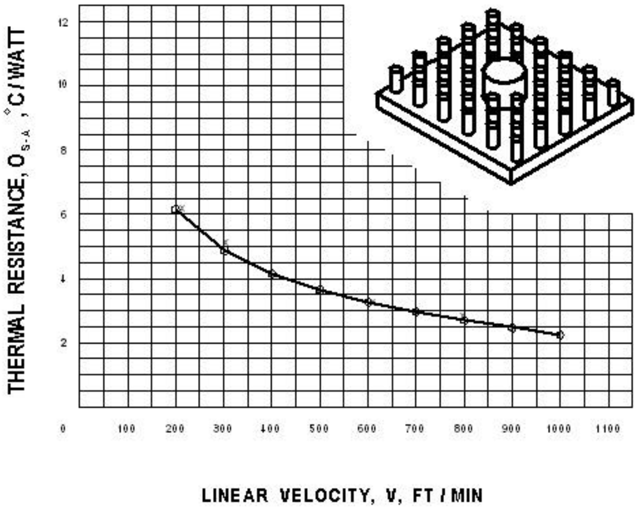
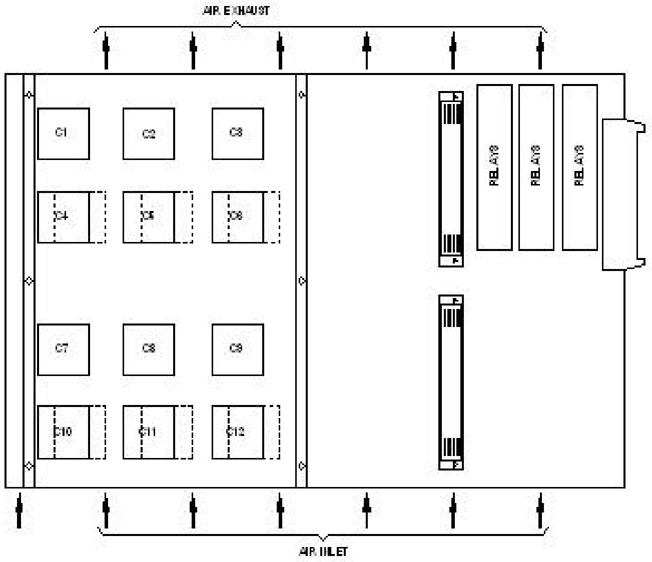


Figure 4: Teradyne pin fin heat sink

The initial effort with respect to heat sinks was to consider a typical extruded fin heat sink, with cross-cuts to turn it into a pin fin heat sink. However, further requirements, such as a vacuum lifting pad at the center of the heat sink for component repair/removal, forced a change to a die casting heat sink. This yielded an additional gain in heat removal due to the die cast process. An advantage of the die casting over the cross-cut extruded pin is that pins that are die cast as cylinders, rather than the square or rectangular cross-cut pins of an extrusion, provide a lower air flow resistance or pressure loss. In selecting the material for the heat sink, materials reviews showed a large degradation in the thermal properties of the die cast aluminum alloys versus the extruded aluminum alloys. Further, it was noted that the thermal properties of the Zinc alloy, Zamak 3, which ultimately was the selected die cast material , were very similar to that of the die cast aluminum alloys.

The thermal characteristics of the pin fin heat sink are shown in Figure 4. The TETS system air flow design currently has linear velocities in the range of 800 to 1000 feet per minute, giving the heat sink a surface to air thermal resistance of approximately 2.5 degees C per watt. The heat sink is attached to the component with a silver loaded epoxy.



ASIC COMPONENT LOCATION	CASE TEMP - NON STAGGERED @25 °C @10 CFM	CASE TEMP - STAGGERED @25 °C @10 CFM
C1	82°	78°
C2	68°	80°
C3	94°	80°
C4 *	74°	82°
C5 *	81°	82°
C6 *	74°	84°
C7	80°	78°
C8	80°	83°
C9	77°	79°
C10 *	61°	70°
C11 *	64°	69°
C12 *	65°	66°

* INDICATES COMPONENTS STAGGERED

Figure 5: ASIC layout alternatives

As shown in Figure 5, the M910 companion board was initially laid out with 12 custom ASICs lined up one behind the other in four columns. After extensive testing it was determined that the temperature of the components at the exhaust side of the board, C1, C2 and C3, were too hot. C3 in particular was running at a case temperature of 94 degrees C. It should be noted these tests were run at an ambient of 25 degrees C and a flow of 10 cubic feet per minute, while the TETS system runs considerably more than 10 CFM through the channel cards and has a maximum operating temperature of 55 degrees C. The board layout was examined in an attempt to reduce the relatively high temperatures in the last row. It was decided to stagger some of the components to allow more air to reach the top components. Components C4 through C6 and C10 through C12 were moved a predetermined distance to the right. This lowered the temperatures of C1 and C3, at the expense of a reasonable increase in the temperature of some of the components in the first three rows. The result was that the hottest components were running cooler and the cooler components were running slightly warmer, which increased the thermal reliability of the design.

Additional considerations were made in component layout in order to make the best use of the air flow that was available, based upon an analysis of the path that the air would take from the chassis through the board to the outlet. Low power components that required less cooling, such as relays, were placed in areas of the board that would receive less air flow. In some instances, higher profile components and varying height heat sinks were used to channel air on the surface of the board towards the higher power devices. Devices that could not be adequately cooled using the available air were fitted with heat sinks that were custom designed to dissipate heat into the PC board.

Other mechanical considerations were made in the design of the M910 to facilitate cooling. The M910 modules have completely open bottom and top panels to maximize the area that air can enter and exit the modules, thereby minimizing any air flow restriction. Board stiffeners, added to enable the M910 to withstand shock and vibration, were strategically placed to aid in the ducting of the air. Additionally, the positioning of the main board and the companion board within the VXI slot was aligned to maximize airflow between the two cards.

IV. CHASSIS POWER INTEGRATION

As with cooling, the VXI specification leaves it to the system integrator to ensure that the instrument chassis can supply enough power to meet the demands of the selected instrumentation. The specification does specify voltage tolerances and ripple limits but current is not guaranteed to be any specific value.

Based on the analysis of current draw vs. current available and the desire to have a modular power supply, the integral HP supply was abandoned and an external supply was shared by both the Primary Chassis and the Secondary Chassis. Sharing helped minimize size and weight while the external approach allowed for a modular design (see Figure 6), which improved maintainability. Additionally, the power supply is a major source of heat. Moving it to a separate chassis eliminated the possibility of it affect-ing the operating temperature of the VXI modules.

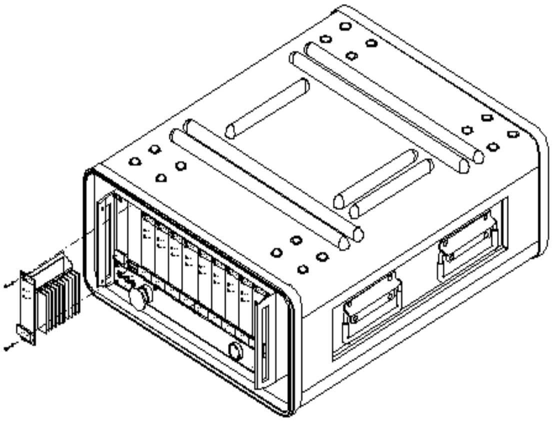
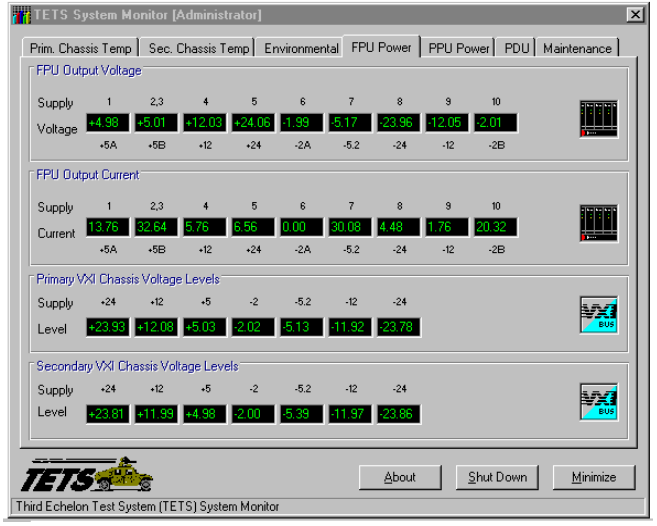


Figure 6: TETS power chassis

To provide for the requirements of the two highly populated VXI chassis, a total of 10 power supplies were used to supply the 7 VXI backplane voltages. Two of the extra units were used to supply the +5 V requirements, with the remaining extra unit going to the –2 V supply. This distributed power scheme allowed all VXI instruments to be fully powered with additional headroom for future expansion.

The requirement for the system to operate from 28VDC dictated that DC/DC converters be used to efficiently convert the 28VDC to the seven different VXI backplane levels. A Vicor-based design was chosen since Vicor has a reputation for reliability and provided the densest power solution. The Marine Corps dictated an operating efficiency of at least 80% and the Vicor design easily achieved an efficiency of between 80% and 90%. This allows it to have a cooler operating temperature, which leads to long-term reliability.

Another advantage to using the Vicor design was its built-in monitoring features. It is capable of reporting the voltage level of each backplane supply along with the current drawn from each supply. This feature made it easy to verify that the entire system had enough headroom when fully populated. The back-plane voltage and current values are read back to the system monitoring software and are available to the operator or maintainer, as shown in Figure 7.



FPU Output Voltage

Supply	1	2,3	4	5	6	7	8	9	10
Voltage	+4.98	+5.01	+12.03	+24.06	-1.99	-5.17	-23.96	-12.05	-2.01
	+5A	+5B	+12	+24	-2A	-5.2	-24	-12	-2B

FPU Output Current

Supply	1	2,3	4	5	6	7	8	9	10
Current	13.76	32.64	5.76	6.56	0.00	30.08	4.48	1.76	20.32
	+5A	+5B	+12	+24	-2A	-5.2	-24	-12	-2B

Primary VXI Chassis Voltage Levels

Supply	+24	+12	+5	-2	-5.2	-12	-24
Level	+23.93	+12.08	+5.03	-2.02	-5.13	-11.92	-23.78

Secondary VXI Chassis Voltage Levels

Supply	+24	+12	+5	-2	-5.2	-12	-24
Level	+23.81	+11.99	+4.98	-2.00	-5.39	-11.97	-23.86

Third Echelon Test System (TETS) System Monitor

Fig. 7: Backplane voltage and current monitoring system

M910 Power Design

A variety of techniques were employed in the design of the M910 in order to reduce the power draw of the instrument. At the component level, the M910 uses primarily CMOS technology to ensure that the maximum power draw was achieved only under active, or “bursting,” conditions, thereby reducing the quiescent power draw. Low power 5 Volt relays that are custom manufactured for high reliability were used in place of traditional 12 Volt relays. Additionally, the pin electronics ASIC on the M910 was redesigned to reduce its quiescent power draw.

Power is distributed to the pin electronics on the M910 using a DC-to-DC converter rather than a voltage regulator. This allows the M910 to draw power from the +/- 24V supplies on the VXI backplane, which are less heavily utilized in most applications. The supply voltages are converted to a single rail, which is then distributed to the logic on the board. By choosing a DC-to-DC converter, Teradyne hardware engineers were able to optimize power specifically for the M910, using the minimum power required to guarantee performance specifications. As an additional benefit, using a converter rather than a regulator means that there is no wasted power, to within the efficiency specification of the converter. The DC-to-DC converter in the M910 has an efficiency specification of 87%, thus very little of the power drawn by the M910 goes to waste.

V. SHOCK AND VIBRATION PROTECTION

The TETS system was specified to conform to the requirements for Type II, Class 3, Style C equipment as outlined in MIL-T-28800E. This specification describes an operating environment with significant levels of shock and vibration, which required special attention to protect the COTS VXI modules. More specifically, the system had to protect against an 11ms, 30G half-sine shock pulse, 10 transit drops of 8 in., loose cargo bounce, and random vibration of 3G. To afford the necessary protection, a combination case was designed to be an integral part of the system. The four main units, 2 VXI chassis and 2 PDU chassis, each were housed in separate cases to keep the weight of each piece to a minimum. Each piece of the system, down to the screws, was chosen with weight being one of the most important factors. This eased the burden on the combination cases, as all four units each weighed less than 100 pounds without the cases.

The cases required shock mounts to protect the equipment, and there are two basic choices, elastomeric mounts and helical coils. The lightweight design of each unit allowed elastomeric mounts to be used effectively. This provided an additional weight savings of approximately 12 pounds per unit over helical coils, which when applied across the system results in an approximate savings of 50 pounds. Eight shock mounts were used on each unit and positioned as shown in Figure 8.

The combination case was a compression molded composite design consisting of fiberglass and Trevira. This material and molding technique provided an excellent strength to weight ratio with the heaviest case weighing just 18 pounds. The composite approach, which allowed for performance over a broad temperature range without sagging or distortion, was far superior to aluminum, which weighed more, or plastic, which was structurally weaker.

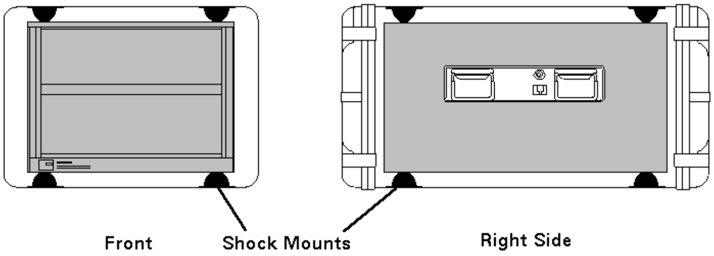


Fig. 8: TETS chassis shock mounts

The M910 is designed for military as well as commercial environmental conditions. As such, the vibration characteristics of the module were given significant attention. The M910 consists of two boards, a main board and a companion board, separated by approximately .65 inches. The boards are about the same size and are tied together in four areas: 2(.25 in. wide by .62 in. high by 9 in. long) aluminum stiffeners, a front panel and 2 (128 pin DIN) interconnect connectors. The stiffeners and connectors are depicted in Figure 5. The front panel is not shown. The mechanical combination of the attachment provided by the four described areas forms a ruggedized box/frame structure. This intent of this structure is to provide a reasonably high natural frequency. The natural frequency of the M910 is approximately 150 Hz. The resonant frequencies of most systems, chassis, or enclosures normally are below 50 Hz. The resulting dynamic deflection of the M910 at the resonance of the chassis or enclosure is minimal. This translates into less stress on component leads and higher reliability.

VI. CONCLUSION

The emergence of standards such as VXI has simplified systems integration by providing a means by which suppliers can describe the attributes of their products using terms and units that are consistent across product lines. This does not, however, relieve the systems integrator from the responsibility to apply those standards at the system level to provide a complete solution. The TETS system couples the use of open standards with a system architecture approach in mechanical, hardware, and software design to provide a complete solution. The resultant design has been proven through exhaustive environmental testing to meet the challenges of the Marine Corps environment.