Thermal Trends and Improvements for Rugged COTS Cards

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Thermal management of rugged COTS (commercial off-the-shelf) cards destined for defense applications has always been a challenge due to the high operating temperatures and other harsh environmental requirements. Add to this the demands for ever increasing functional density, achieved by using the latest processors and dense packaging, and the abilities of the incumbent cooling approaches (air and conduction) are pushed to the brink. Fortunately, the increasing challenges continue to be met with air and conduction cooling innovations. For power dissipations or densities beyond these limits, liquid flow-through (LFT) module designs offer a large step increase in cooling capability with plenty of headroom for the foreseeable future.

Thermal Trends

Figure 1. An air-cooled heat sink with offset fins.

At the processor die level, Moore’s Law dictates that ever smaller transistors are used to increase functional density, and they are run at ever higher frequencies. Both of these trends increase heat dissipation. Further increasing waste heat is current/power leakage. Leakage was always present in the total power calculation, but has recently become a major concern due to the miniscule geometries of the ever smaller transistors.

As somewhat of a counter-balance, lower core voltages and the recent trend to multiple processing cores reduce heat and heat density, respectively. Also, Intel has announced the use of new transistor materials on their next-generation processors that promise to substantially reduce leakage power. Finally, power management techniques are being architected into processors for even further power decreases. It remains to be seen whether these power reduction approaches will be enough to alleviate the traditional power increases seen to date.

At the plug-in module level, trends show increasing power and heat loads, particularly for high-processing-density DSP (digital signal processor) modules, which have seen an exponential increase in power over the last decade. Power increases are likely to continue with the introduction of new high-speed serial technologies via the new VPX specification (VITA 46). VITA 46 allows up to 768 Watts of power to be brought onto a 6U x 160-mm module. This is a huge increase over the 90 Watts allowed on VME cards, and poses a substantial cooling challenge to thermal engineers. In addition, the new VPX-REDI specification (VITA 48) allows a 1" pitch with increased space available for taller, and typically hotter, components.

Cooling Solutions at the Plug-In Module Level

Cooling military COTS electronics has typically been done through either conduction or air cooling, or a combination of both; for example, avionics chassis with forced-air-cooled sidewalls cooling conduction modules inside the chassis. Airflow over electronic components is also used for cooling; however, the modules are not as rugged under military conditions like shock and vibration as conduction modules.

For air-cooled modules, the simple convection equation (Newton’s law of cooling) can be used to determine where effort should be focused for improvements in cooling.

$$Q = h \square A \square \Delta T$$

Where Q is heat load in Watts, h is the heat transfer coefficient in W/m^2K, A is area exposed to the air flow, and ΔT is the temperature difference between ambient and the surface being cooled.

In most cases, ΔT is fixed because there is a maximum component junction temperature and a maximum ambient temperature. To increase the amount of heat that can be cooled, either *h* or *A*, or both, need to be increased. Increases in *A* usually take the form of finned heat sinks placed in contact with hot components. This introduces conduction heat transfer as a factor between the die and the heat sink surfaces. The various resistances in this conduction path need to be accurately determined and modeled for the computational fluid dynamics (CFD) thermal analysis. In particular, any thermal interface materials (TIMs) need to be characterized because datasheet thermal conductivity or resistance values have been found to be as much as an order of magnitude too optimistic compared to independently measured values.

Increasing the heat transfer coefficient can be done in several ways. The most straightforward has been to increase air velocity over the surfaces being cooled. This can be done with higher flow/pressure fans and blowers, or by channeling existing airflow to hot components. Other approaches to increasing *h* include offset fins (Figure 1), which re-introduce airflow boundary layers, and dimpled fins, which introduce boundary layer disturbances.

Conduction-Cooled Modules

For conduction cooling, the simplest form of Fourier's law of conduction can be used to highlight cooling improvements:

$$Q = k\square A\square(\Delta T/\Delta x)$$

where k is thermal conductivity in W/m°K, A is cross-sectional area perpendicular to heat flow, and Δx is the heat path length. Increases in A and decreases in Δx are limited by form factor envelopes, component layout, and component density. The new VPX-REDI specification (VITA 48) helps here by introducing a 1" pitch and allowing card edge retainers on the secondary side of the module.

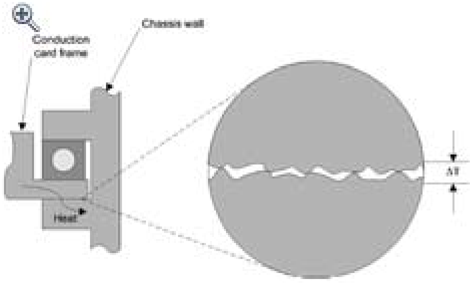

Figure 2. Thermal contact resistance between the conduction card and chassis rail.

Thermal conductivity increases can be achieved with different materials; e.g. copper instead of aluminum, although weight constraints typically limit copper's use to small areas. Composite materials hold promise in being able to increase thermal conductivity without excessive, or in some cases any, increase in weight. One issue with some of these materials such as aluminum-graphites, is their very low "through thickness" conductivities as compared to "in plane" (very high). In some applications, this may be acceptable and still result in overall cooling improvement, while in others no cooling benefit is obtained. An accurate finite element thermal analysis is required to determine this. In addition, characterization of material properties is highly recommended to ensure you get what you pay for.

Very high effective thermal conductivities may be obtained through the use of heat pipes due to their use of liquid-to-vapor phase change. The increased conductivity is only in the axial direction of the heat pipe, and they are orientation-dependent due to body force effects on the condensate. Nevertheless, innovative embedded heat pipe designs have been developed to increase cooling and operate in harsh military environments.

A perceived drawback to conduction-cooled modules is the thermal contact resistance that arises between the module's card edges and the chassis rails, which they contact (Figure 2). Values between 0.3 to 0.5°C/W have been used for 160-mm deep cards (per card edge), meaning that temperature deltas of 15 to 25°C for a 100-W module are lost at this interface. Experimental characterization of various surface finishes and properties has shown that contact resistance values can be reduced substantially from the above values.

For both air-cooled and conduction-cooled modules, continuous innovation as described above has resulted in sustained increases to the amount of heat that can be cooled from military COTS modules with given boundary conditions. For 6U air-cooled modules at 70°C inlet air temperature and conduction modules at 85°C card edge, 200 W was previously considered virtually unobtainable. Now that target is in sight, with over 160 W being achieved recently. The price being paid, however, is a dramatic increase in the time and resources required for thermal design, analysis and testing.

What’s Next?

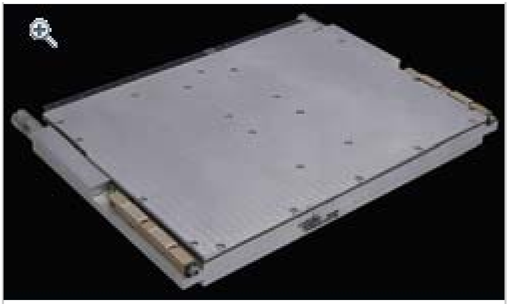

Figure 3. A liquid flow-through (LFT) module capable of cooling 650+ W.

Air cooling and conduction cooling will continue to have incremental gains; however, there is a need for a large step increase in cooling ability for future designs and to provide cooling headroom. Liquid flow-through (LFT) cooling at the circuit-card level has been proven to be able to cool at least 650 W (PAO coolant, 55°C inlet, <15 psi drop across module) with four 100- 150 W heat loads on a 0.85" pitch, VITA 48.3 module (Figure 3). This kind of performance qualifies LFT as the next step in cooling for military COTS modules.

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