COTS – revolution, evolution or devolution?

Dr Carlo Kopp

> In terms of providing access to the latest high performance processor hardware and software, it is revolutionary; in terms of adapting to a fast changing environment, it is evolutionary; and in terms of meeting specialised military needs in environmental hardening and reliability, it can be a devolution if not handled carefully.

The Block 35 F-22A uses PAO liquid cooling for core mission avionics, and COTS processing hardware in several key systems.

LARGE scale usage of COTS (Commercial Off The Shelf) computing hardware in military systems has become pervasive, and is mostly a stated requirement for new systems. Is this a revolution, evolution, or devolution?

COTS technology is not a panacea for military computing applications but if used correctly can overcome endemic problems that have plagued such applications for decades. Military embedded applications are some of the most environmentally challenging in which any computing equipment must survive, and many military operating environments can be as harsh, or harsher, than space operating environments, the accepted benchmark for extremely harsh operating conditions.

Why COTS computers?

When the Cold War ended the global computing landscape was a very different place than it is today. Commercial computers were built for civilian users and military computers for military users, with very little overlap between the two. The US military, the biggest user of military computing equipment, developed and built its own hardware standards, and computer languages. The US Air Force for instance used 16-bit Mil-Std-1750A architecture machines similar to the earlier commercial PDP-11 series, typically programmed in the JOVIAL high level language or directly in machine-level assembly code. The US Navy and Marines had their own equivalent but different AYK/UYK-14 (Yuk-14) machines. Then the US DoD decided to reduce software maintenance costs by mandating the ADA high level programming language for all new military software, whether embedded code in weapon systems, or accounting packages. ADA was derided by computer scientists of that period, seen as a cumbersome attempt to do too many diverse things with a single tool.

Compatibility of hardware was a headache, as military computing equipment generally did not interface at a hardware level with mainstream commercial hardware. The commercial world at that time relied primarily on the C and C++ programming languages, with Fortran dominant in engineering/scientific software, and COBOL in commercial software. This polyglot environment was further complicated by a plethora of different commercial machine architectures in use, dominated by SPARC, MIPS and DEC Alpha in the technical computing areas, Intel i86 and Motorola 68K in the industrial embedded and desktop computer markets, along with a range of legacy commercial minicomputer and mainframe architectures, dominated by IBM and DEC VAX-11/PDP-11.

Two problems emerged, both intractable and expensive. One was maintaining software across systems through lengthy life cycles in languages often not widely used, and the difficulty in recruiting programmers with experience in their use. The other was in dealing with increasingly short hardware life cycles, as exponential growth through Moore's Law reduced the production life of any computer chip year by year. The classic example is in the development of the F-22A Raptor: by the time the aircraft entered production many of the computer chips used initially in the design had to be replaced as they were no longer in production.

A reality of Moore's Law is that if specialised military computers lagged their commercial cousins over two or three years, the lag in computing performance grew exponentially over time. By the latter 1990s the increasing gap between the performance of custom built military computers and mass produced commercial computers left military users at a serious disadvantage, precisely during the very difficult period of fully 'digitising' Western military equipment, and deploying digital networks to effect Network Enabled Operations.

While ADA language and specialised military computer architectures had their advocates it was clear that the model evolved through the Cold War could not be sustained over time, as it was incompatible with a Moore's Law driven world.

This resulted by the late 1990s in two important developments, the first being the widespread use of 'ruggedised' COTS computers in less challenging military applications. A standard commercial computer was repackaged into a hardened military chassis equipped with compatible interfaces to military power and cooling environments. Typically, such systems ran commercial operating systems and often applications including Microsoft Windows or Unix/Linux variants. Ruggedised computers remain a mainstay in military computing applications, especially where a widely used civilian software application is deployed in an operational environment or platform.

The second development was an outcome of the Bold Stroke and Oscar trials when state-of-the-art commercial processor chips were integrated into military equipment, primarily by adapting industrial grade VME standard hardware to produce defacto MilSpec computing equipment but compliant with commercial interfaces and standards. These trials also involved development of software in the dominant commercial C and C++ languages. C was developed for coding operating systems and remains the language of choice in industrial embedded applications, as C language code can be made to execute very quickly, and permits easy manipulation of computer hardware. C++ language evolved from C, or provide an Object Oriented (OO) capability, important for applications with high levels of modularity. The trials were successful and resulted in a large scale shift across to C/C++ and commercial MIPS and Motorola PowerPC chips in new military applications. The PowerPC is better known as the chip used in Apple Mac G3/G4 machines.

When the term COTS is used to describe an embedded military system, more than often it refers to these technologies.

Maintenance of legacy software and hardware however remained a problem, since rewriting hundreds of thousands of lines of code from JOVIAL, or Mil-Std-1750A or UYK-14 assembly language, then retesting and validating the code, can be almost as expensive as developing the code anew. For a major weapon system, this is not trivial.

Two approaches have been used to overcome the obsolescence of legacy 16-bit hardware. The first was to manufacture new design Mil-Std-1750A processing chips, which run the legacy software with no limitations. These chips may have tenfold the performance of the original 16-bit hardware they replace, but typically cannot compete with contemporary commercial 32-bit and 64-bit processor chips running at 3 GigaHertz.

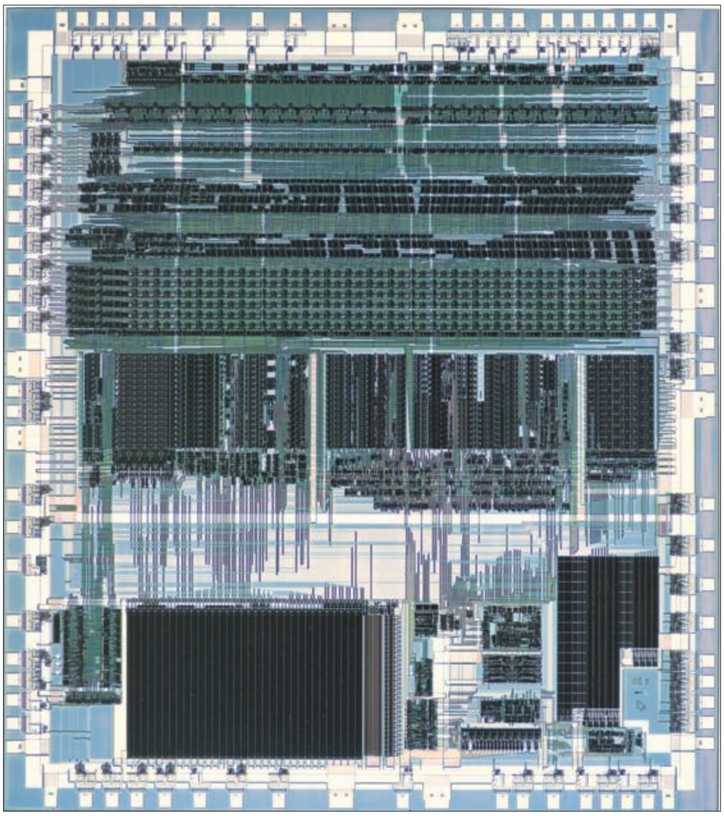
A more sophisticated solution was the development of software emulators for the Mil-Std-1750A machine, which could be run on much faster commercial chips. A single PowerPC chip running at GigaHertz class speeds could for instance emulate hundreds of 16-bit Mil-Std-1750A chips concurrently, and have computing cycles to spare. This technology is also the basis of 'cloud computing', where arbitrary hardware is emulated in software.

Emulation is especially powerful, as it provides a low cost migration and growth path for legacy embedded systems. A COTS processing system involving for instance a VME chassis loaded with PowerPC processors can become a 'drop in' replacement in the volume of a legacy 16-bit Mil-Std-1750A embedded minicomputer, with no software changes for legacy code in the system, but providing additional capacity to add new code.

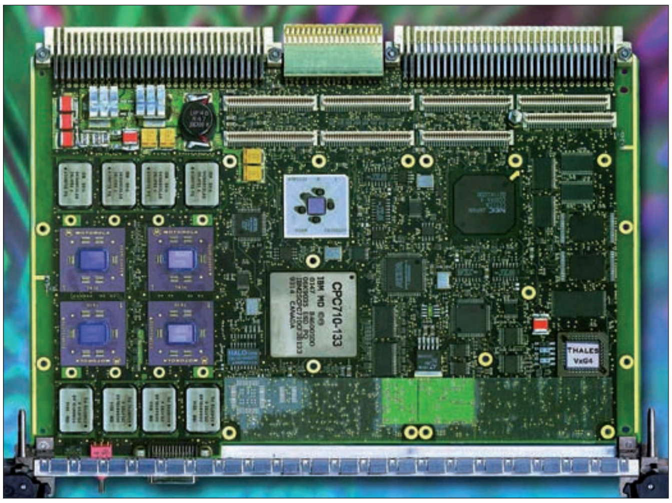
The question as to whether COTS computing is a revolution, evolution or devolution could perhaps best be described as having elements of all three. In terms of providing access to the latest high performance processor hardware and software, it is revolutionary; in terms of adapting to a fast changing environment, it is evolutionary; and in terms of meeting specialised military needs in environmental hardening and reliability, it can be a devolution if not handled carefully.

Harsh military environment problem

Installing any electronic hardware into a military system such as an aircraft, ground vehicle, warship or guided munition exposes this hardware to the full gamut of environmental stresses inherent in the operating conditions in which the system must survive. The problem is not unique to computer hardware, or even electronic hardware, and generally applies to all components.



Pyramid Semiconductor P1750AE enhanced Mil-Std-1750A processor chip for military and space applications.



VMEbus embedded systems dominate current military COTS applications, an example is this Thales PENTXM card.

Electronic hardware, especially computers, is however especially critical from a reliability and functional integrity viewpoint, since more than often they sit at the core of the system, driving guidance, control, communications, networking and system management tasks. Moreover, they are increasingly embedded into subsystems, hidden away where they perform critical control, management and diagnostic functions. If the embedded computer fails or misbehaves, the subsystem also more than often fails or misbehaves.

This is not a new problem, and first caused difficulties during the 1940s when electronic, precision optical and mechanical hardware was incorporated into military systems on a large scale. The result by the late 1940s was that the mathematics of equipment failures were studied and understood, resulting by the 1950s in the establishment of formal Military Specifications (MilSpecs) in the United States and later STANAG NATO standards, in which a formal methodology was adopted so that reliability of military systems could be studied, measured, predicted in designs and validated by testing. The US MilSpec system was mandatory through the Cold War era and did not unravel until the 1990s when budgetary pressures and contractor lobbying saw most of the MilSpecs abandoned as a formal requirement when purchasing military equipment. Engineers in the contractor community more than often continue to use these standards when equipment is being designed to survive in harsh military environments. The key standard in this area is Mil-Std-810.

How harsh are military operating environments? Military operating environments differ, and often differ strongly. Equipments embedded in aircraft, ground vehicles, warships or guided munitions are exposed to different conditions, inevitably reflecting the platform environment.

Operating temperatures are a major problem, as are thermal transients, where hardware is rapidly heated or cooled during operation. Thermal problems are usually both electrical and mechanical in nature, and frequently not easy to solve effectively.

High operating temperatures degrade the reliability of solid state electronic components like chips, often catastrophically. The mechanism is submicroscopic, and prolonged high temperature operation cause the semiconductor structures in the chip to progressively erode. At some point this results in failure, which in severe cases literally causes the chip to melt down into a puddle of Silicon, or other material.

Keeping chips cool is thus essential to reducing failures. Cooling is mostly performed by blowing air over the components, which may have finned heatsinks attached to improve effect. More recent techniques include conduction cooling, where heat is drawn out through a metal component and transferred into a chassis, or liquid cooling, where water or Poly-Alpha-Olefin (PAO) coolant is used to transfer heat away. The latest approach in aircraft is to combine conduction and liquid cooling, and then dump the heat into the aircraft's fuel tanks – a scheme which performs well when the tanks are full but not so well when low.

Ground vehicles and aircraft frequently present the most extreme thermal environments. Ultimately, the heat dissipated by the chips has to be dumped outside the platform housing the equipment. If the system design cannot achieve this, the chips run hotter and fail more frequently.

Thermal transients are a problem in their own right, resulting in various types of failures. While these might manifest as electrical failures, they are mostly mechanical failures. If two components attached together expand or contract mechanically as they are heated or cooled, but do so at different rates, enormous mechanical stresses can develop. The result can be printed circuit boards delaminating, electrical connections snapping off, or chips shearing off substrates.

Airborne, missile and space applications present the most challenging thermal transient environments. Guided missiles often exhibit such failures, as they might be cold soaked to deep sub-zero temperatures while hanging off a pylon on an aircraft, upon which they rapidly heat up in flight once launched as temperature inside the missile builds up, and heat cannot easily escape.

Mechanical vibration and shock loading is another feature of military operating environments that can impair electronic equipment. Vibration, which involves cyclic mechanical loads can be especially destructive, as metal and plastic will eventually fracture due to mechanisms much the same as those causing fatigue failures in aircraft structures. Circuit boards in electronics and computers will often become excited by vibration, and flex in the manner of a drum membrane.

While ground vehicles, especially tracked vehicles, are usually associated with intensive vibration and shock loads, the former can occur in aircraft and was a known cause of missile failures when carried on particular stations on aircraft. Carrier based aircraft are an unfriendly environment for shock loads, especially for munitions.

Moisture and humidity, especially where salinity is involved, can have highly destructive effects on electronic equipment, primarily due to corrosion of metals such as copper and silver used in contacts. While gold plating contacts is an excellent fix, it has despite affordable costs been often seen as 'gold plating' the equipment. More subtle problems can occur however, especially in tropical environments where the epoxy resin used to package commercial chips and other components can permit moisture ingress, resulting in internal corrosion problems. Naval equipment is most frequently associated with such failures, but ground equipment and aircraft especially in tropical or littoral environments experience the same problems.

Fine sand and dust presents known problems in desert operating environments, if allowed to enter equipment. It can clog air cooling systems, filters and heatsinks, but also cause abrasion damage to gold plating on contacts. A more subtle problem arises when high velocity dust impacts equipment in dry air, as electrostatic discharges can occur, which may cause fatal electrical damage – the charge being coupled into equipment via antennas or exposed cabling. The well known glowing night-time discharges on helicopter rotors, dubbed the 'Kopp-Etchells Effect' are another manifestation.

Electronic equipment, especially computer circuit boards, constructed to traditional US MilSpecs, and intended to survive in harsh military environments, but therefore need to be constructed quite differently from commercial equipment.

Typical features include much smaller and thicker circuit boards, or ceramic chip carriers, mechanical stiffeners attached to circuit boards, shock and vibration absorbing mountings, ceramic rather than plastic chip packages, generous use of gold plating, and a host of other measures. A functionally equivalent MilSpec computer board or computer, which must be heavily tested before released from the factory, may often cost several times what its commercial cousin might.

An intermediate level of 'hardening' is seen with 'ruggedised' COTS equipment, where generic civilian commercial grade computer circuit boards are modified and installed into MilSpec grade chassis. While not as robust as 'full MilSpec' such designs are often more than adequate for less challenging military applications.

Ground vehicles, especially tracked vehicles, present not only challenging thermal environments, but also difficult vibration and shock loads.